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Soil characteristics of the deciduous forests in Central Ontario and their relationships with site indicies of sugar maple, American beech and red oak

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Soil Characteristics of the Deciduous Forests in Central Ontario and their Relationships with Site Indices of Sugar Maple, American Beech and Red Oak

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ABSTRACT

Rahi, A.A. 2004. Soil characteristics of the deciduous forests in central Ontario and their relationships with site indices of sugar maple, red oak, and American beech

Key Words: Algonquin Park, American beech, central Ontario, Haliburton Forest, North Bay area, red oak, soil characteristics, soil moisture regimes, soil nutrient regimes, soil-site index relation, Sugar maple.

Tolerant hardwood forests occupy a broad geographic range in Ontario and they are important for their ecological and economical values. Although sugar maple (*Acer saccharum* Marsh.), American beech (*Fagus grandifolia* Ehrh.), and red oak (*Quercus rubra* L.) are among the most common species in these forests, our knowledge about their ecological factors is limited. Also, local foresters have to use models developed in other regions to predict the quality and productivity of sites associated with those hardwood species.

In this study, 61 plots of sugar maple, American beech, and red oak were established in Algonquin Park, Haliburton Forest, and North Bay area. At each plot 3-9 undamaged dominant study trees with no indication of previous disturbance were felled for stem analysis and producing site index. At each plot, three soil pits were dug and soil samples from H, A, and B horizons were collected. Physical characteristics including texture, coarse fragment content, thickness of horizons, and depth of rooting system and chemical characteristics including pH and both concentration and pool of C, N, P, Ca, Mg, Na, and K were measured.

In the second chapter, the measured variables were compared/contrasted among the study species. In almost all cases, significant differences were found between beech and red oak, while sugar maple was associated with either of them. Beech and sugar maple occurred on deeper soil with higher pH, P, Mg, and Ca in A horizon and silt content, pH, Ca, and P in B horizon. Also red oak and sugar maple were found on soils with higher C:N ratio and P in H horizon and lower N and Na in H and A horizon and Na in B horizon.

In the third chapter, the soil variables were used to produce appropriate models to indirectly estimate site index of three study species in the region. The samples for sugar maple were stratified into three regions and the best models had R^2 of 0.51, 0.50, and 0.94 for Algonquin Park, Haliburton Forest, and North Bay area respectively. Also, the regression models for red oak and beech had R^2 of 0.73 and 0.72 respectively.

In the fourth chapter, the nutrient concentrations were compared/contrasted within site quality classes of study species in order to find possible trends which could be used in quantifying soil nutrient regime (SNR). American beech was found to be a better site species indicator since more nutrients had linear trend within its site quality classes. Moreover, P concentration was found a better element for quantification of soil nutrient regime. Soil moisture regime (SMR), on the other hand, showed no linear relationships with site quality classes of any of those three species.

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To my mother and the memory of my father

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CHAPTER 1. INTRODUCTION TO THE THESIS

1.1. INTRODUCTION

Tolerant hardwood forests in central Ontario occupy part of the Great Lakes - St. Lawrence region and are distributed over more than 3.6 million hectares. They are characterized mainly by species such as sugar maple (*Acer saccharum* Marsh.), red oak (*Quercus rubra* L.), American beech (*Fagus grandifolia* Ehrh.), white ash (*Fraxinus americana* L.), black cherry (*Prunus serotina* Ehrh.), and basswood (*Tilia americana* L.) associated with eastern hemlock (*Tsuga canadensis* (L.) Carrière), yellow birch (*Betula alleghaniensis* Britt.), and white and red pine (*Pinus strobus* L. and *Pinus resinosa* Ait.) (Rowe 1959). Forests in central Ontario also provide a variety of high quality materials for local industries and have important impacts on the economy of Ontario. The economic values along with their ecological, social, and cultural impacts have made tolerant hardwoods a crucial element in daily lives of people of one of the most populated areas in the country.

The diversity of wildlife found in these forests is also an important consideration within the context of forest management planning. The number of species in present time and the ideal composition in the future represent the basic underpinning of sustainable forest management. For example, studies suggest that during the last 100 years the abundance of sugar maple in maple-dominant stands has increased at the expense of yellow birch and conifers (OMNR 1998). Foresters, in response to these species shifts, need to decide whether to apply silvicultural methods to at least maintain the current species composition or apply silvicultural techniques to enhance yellow birch representation. Such a task will not be possible without understanding the ecology of the dominant species and their interrelations at the site/soil level. Also, with an increase in intensive forest management (IFM), additional challenges in terms of site quality estimation are likely to emerge.

During the last decade, social, cultural, and economical values of forests have had a strong influence on the management of Crown forests in Ontario, and have redirected management planning to focus on the goal of sustainable forest management (SFM), which is defined as "... maintaining and enhancing the long-term health of our forest ecosystems, for the benefit of all living things both nationally and globally, while providing environmental, economic, and social, and cultural opportunities for the benefit of present and future generations" (OMNR 2002).

Within the above-mentioned context, the tolerant hardwood forests of Ontario continue to play an important role in "sustainable forestry" by producing a variety of forest products including high quality lumber while maintaining productive capacity, site quality, wildlife habitat and biological diversity. They occupy a broad geographic range in Ontario with noticeable high-value products (OMNR 1998). High quality hardwood lumber is usually used in a variety of products such as furniture, flooring, paneling, tie, pallet and in the coffin industry, while a lower grade of products include pulp and fuel woods. As a result, the value differential to log quality is significant, for example, grade 1 tolerant hardwood sawlogs may have over 30 percent more dollar value than grade 2. A quality veneer log may have more than double the commercial value of a similar sized sawlog (OMNR. 1998). Among the hardwood species, sugar maple, American beech, and red oak are the major components of the tolerant hardwood forests contributing 43%, 4%, and 3%, respectively, of the total harvest of region (Anderson *et al.* 1998). Therefore, the improvement in both quality and quantity, via forest management and silvicultural practices will increase the economical impacts of tolerant hardwood forests.

Ontario's Living Legacy, as sponsor of this study, funded a project in 2001 to develop site-quality evaluation tools for the deciduous forests of central Ontario. In this thesis, three main subjects are discussed. Under the first subject (Chapter 2) the soil characteristics of the region under sugar maple, American beech, and red oak stands were investigated. The null hypothesis was that the soil characteristics under all three study species were similar. To examine the hypothesis, the measured soil characteristics in each horizon under study species were compared/contrasted to each other and those with significant differences were identified. This information provides insight into the soil chemical characteristics of the region and their role in defining forest composition of the deciduous forests of central Ontario.

In Chapter 3, soil characteristics significantly influencing site indices of the study species were identified and used to develop soil-site models for predicting site indices of the featured species. Since, currently, there are not any soil-site models available for these species in the region, the models should provide useful tools to forest managers for evaluating and predicting of site quality where no suitable tree for direct site index estimation is present.

In Chapter 4, a preliminary approach to develop a soil nutrient regime (SNR), based on measured soil nutrients, was examined. Field ecosystem classification (FEC), as the most common tool for identifying and classifying the forested sites in central Ontario, lacks a quantitative SNR. In addition, FEC has been a poor tool for site quality evaluation, perhaps because the initial data used for classification were not directly related to site productivity. Accordingly, developing a SNR would prove useful for estimating soil nutrients based on simple field characteristics and rapid identification of site quality.

It must be noted that in this thesis the effects of soil on forest composition and tree growth are studied. The impacts of tree species on the soil and their possible abilities to alter the soil characteristics are not studied here, although, some speculations are considered based on other studies in this regard.

1.2. AN OVERVIEW OF THE REGION

1.2.1. Location and Physiography

Central Ontario's deciduous forests are part of the Great Lakes and St. Lawrence region and all materials presented in this thesis are focused on central Ontario unless otherwise mentioned. The northern boundary of Central Ontario extends from Lake Superior, just south of Wawa, south of Chapleau, Gogama and Kirkland Lake to the Quebec border. The southern boundary stretches from Arnprior in the east to Honey Harbor on Georgian Bay in the west. Central Ontario lies within the boundaries of Site Regions 5E and 4E (Chambers *et al.* 1997). This area is part of Great Lakes-St. Lawrence region including 10 forest sections described by Rowe (1959). The sample plots mainly occurred in L.4d: Georgian Bay; and L.4b: Algonquin-Pontiac sections. A small portion of plots were also situated on southern parts of L.4e: Sudbury-North Bay and north of L.1: Huron-Ontario Section.

Physiographic features of Ontario south of North Bay fall into two parts based on bedrock geology. The north section (generally north of the Kawartha Lakes), part of the Canadian Shield, is characterized by knobs and ridges of granite and other rocks from Precambrian age. The south section overlies the Paleozoic rocks which are the softer sedimentary limestones, shales and sandstone (Chapman and Putnam 1984).

As a result, central Ontario's tolerant hardwood forests occur on two distinct bedrock zones. The southern forests occupy fertile, relatively deep soils and limestone. These soils have developed on a wide range of geological material and landforms. The forests to the north occur on less fertile, relatively shallow soils where acid granites and gneisses have weathered to produce coarse to medium sands with low silt content and very small amounts of clay (OMNR 1998). Almost all of the sample plots are located on the north section, the Canadian Shield.

1.2.2. Climate

The region is dominated by a continental climate with cool winters and warm summers. Regional climate, however, is modified by topography and proximity to the Great Lakes (Chambers *et al.,* 1997). Precipitation varies from 550 to 1018 mm per year. Mean annual temperature is between 0.1 to 9.4°C and the mean length of growing season is between 168 to 243 days (MacKay *et al.* 1996).

The effect of climate on the tolerant hardwood forests of Ontario is modified by latitude, aspect, slope, and proximity to the Great Lakes (Chambers *et al.* 1997). The climatic characteristics that significantly affect tolerant hardwoods are the decrease in summer temperature from south to north, and the trend of atmospheric humidity from drier west to more humid east. In addition, weather is quite variable because of the occurrence of storm-tracks of continental-polar and -tropical air masses (Chambers *et al.* 1997).

1.3.3. Silvics

The Great Lakes-St. Lawrence forest region is characterized by white and the red pine (*Pinus strobus* L., *P. resinosa* Ait.), eastern hemlock (*Tsuga canadensis* (L.) Carrière) and yellow birch (*Betula alleghaniensis* Britt.). Within this forest region, the deciduous forests of central Ontario are made up of other broadleaf species including sugar maple (*Acer saccharum* Marsh.), American beech (*Fagus grandifolia* Ehrh.), red oak (*Quercus rubra* L.), white ash (*Fraxinus americana* L.), black cherry (*Prunus serotina* Ehrh.), and basswood (*Tilia americana* L.) (Rowe 1959). Natural disturbances such as wind fall, insect attack, and disease as well as human activities, have also had a major influence on current forest composition. The "Field Guide to Forest Ecosystems of Central Ontario" (Chambers *et. al* 1997) provides an extensive ecological classification of the region.

Silvicultural methods, applied in central Ontario, depend largely on the silvics of each species such as: reproduction (biotic) potential, growth, and tolerance to different ecological site factors (OMNR 1998). The selection harvest system for uneven-aged stands and shelterwood and clearcut systems for even-aged stands represent the major logging methods used in the region.

1.3. RESEARCH METHOD

1.3.1. Study Area

During the summer 2001, 61 temporary sample plots across central Ontario were located near southwestern limit of the Great Lakes-St. Lawrence forest region including the Algonquin-Pontiac (L4b), Georgian Bay (L4d) and Sudbury-North Bay (L4e) Forest Section (Rowe 1972). The study area was subdivided into three administrational units: the southern half of Algonquin Park (AP); Haliburton Forest and Wildlife Preserve (HF); and the portion of crown forest extending north from Huntsville to North Bay, and west from Algonquin Park to Parry Sound (NB) (Figure 2.1). The number of tree inventory plots, soil pits, and soil samples within each forest unit were summarized at Table 2.1.

Table 1.1. Number of sample plots, soil pits, and soil samples (horizons) at each study area.

Area	Plots	Soil pits	Soil Samples
Algonquin Park	22	66	190
Haliburton Forest	22	66	212
North Bay area	17	51	121
Total	61	183	523

1.3.2. Plot Establishment and Data Collection

Sites fully stocked with no indication of recent disturbances (insect attack, clear cut, etc) and the presence of dominant or dominant and co-dominant trees of target species (sugar maple, beech, red oak) of age 50 years at breast height were selected as sample sites. Sample trees were free-growing and uninjured with no suppression during in the past. Forest Resource Inventory (FRI) maps, Permanent Sample Plot (PSP) databases (OMNR) and local foresters' knowledge were used to cover the full site quality array for each species in the region.

At each sample site, a 100 m^2 circular plot with a radius of 5.64 m was established. The diameter at breast height (DBH) of all target species inside the sample plot were measured and recorded. Elevation (m), latitude, and longitude measured with Garmin eTrex Legend Geographic Position System (GPS) in addition to slope pattern (crest, upper slope, middle slope, lower slope, toe, depression or level) of the site were recorded. In addition, soil, vegetation, and ecosite type of each sample plot were also determined based on the "Field Guide to Forest Ecosystems of Central Ontario" (Chambers *et. al* 1997).

Three to nine dominant or co-dominant sample trees for each target species inside the sample plot were selected and felled after examining for evidence of major injury, deformity, or past suppression in the field. After total height was measured in the field, stem discs at zero, 1.0, 1.30 m above the ground and then at 1.0 m intervals from breast height were cut. Then, rings of each disc were counted in two directions until the same count was obtained. At each stage, efforts were made to exclude those sample trees with the evidence of past disturbance or suppression. Nonlinear least square regression method was used to produce site index models (Buda 2004). An average site index values for each plot and species was measured and used in this study.

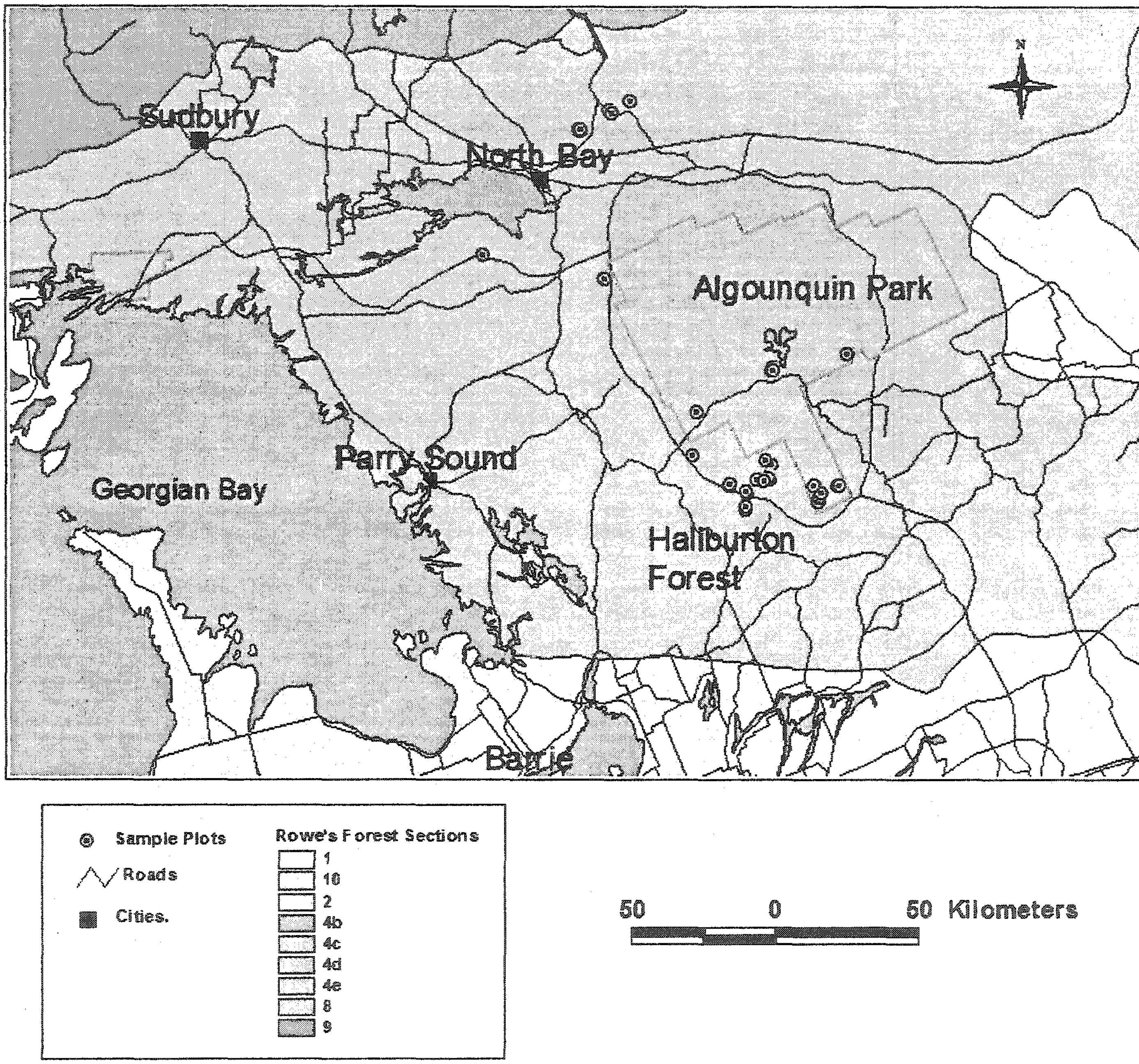

Figure 1.1. Map of central Ontario identifying the three covered regions and the location of sample sites.

1.3.3. Soil Sampling

Three soil pits were located within each tree inventory plot. The soil pits were located in close proximity to the selected stem analysis trees, in order to be representative of the edaphic condition for that tree. In cases where there were more than three sample trees in one plot, the soil pits were located at the center of a group of two or three sample trees.

Each soil pit was excavated with a diameter of at least 1 meter and to a depth of rooting system. Care was taken not to disturb the forest floor and the surface of the soil profile. The depth and abundance of rooting system, the presence of mottles, and the thickness of each horizon were recorded on tally sheets as well as a schematic of the profile. Soil samples were obtained for the H, A, and B horizons where the layer thickness was greater than 3 cm. In addition, two cores were taken from the A and B horizons within each soil pit for bulk density measurement of mineral soil.

1.3.4. Sample Preparation and Laboratory Analysis

Soil samples, immediately after being collected, were air-dried at room temperature (20-25°C) to prevent microbial-induced nutrient transformation. The time period depending on each sample varied from 24 to 72 hours. Pieces of macro-organic matters such as root, debris, wooden objects, and leaves were picked out after air-drying procedure. Mineral horizon samples were then ground to pass 2-mm sieve and the remaining particles larger than 2 mm weighed and the coarse fragment percentage in each sample was determined.

To determine remaining moisture content after air drying, 5 g soil from each sample was collected and dried at 105°C. Then the oven dried soils were weighted and used to calculate the percentage of moisture content. These percentages were, then, used to modify the percentage of organic matter and the concentration of nutrients in the soil samples. Texture of mineral soil samples was determined using Bouyoucos hydrometer method (McKeague 1978). In this method, 10 mL calgon solution was used as reagent for 50.0±2.5 g soil samples. The core samples for bulk density were first weighted and then oven-dried at 105°C. The dried soil samples were ground to pass 2-mm sieve and the volume of both particles larger and smaller than 2 mm were measured by locating them in 1000 ml graduated cylinder. Bulk density for H horizon was assumed to be 0.25 g cm^{-3} (Brady 1990).

Soil pH was measured potentiometrically in a saturated paste of both distilled water and 0.01 M $CaCl_2$ with a soil suspension of a 1:2 mineral soil to liquid mixture and 1:5 for organic soils (Kalra and Maynard 1991). Because pH is negative logarithm of $[H^+]$ ion in solution, all measured pH values were converted to H^+ concentration for all analytical process (e.g., average, regression analysis, etc) and then results were expressed in pH for convenience.

Organic matter was measured by loss on ignition method at 400°C±10° for overnight (16 hr.) The percentage of organic matter in the sample was then multiplied by 0.58 to estimate the percentage of organic carbon. Total nitrogen was determined by digestion method (Karla and Maynard 1991) using 0.25 g for the H horizons and 1.0 g for the A and B horizons. Concentrated H_2SO_4 (18 M), 96% and Kjeltab containing 3.5 g K_2SO_4 and 0.4 g $CuSO_4$ were used as reagents to digest soil sample and convert organic N to NH_4^+-N.

Available phosphorus was determined by Bray 1 (dilute acid-fluoride) procedure since the relatively high acidity of samples. In this method easily acid-soluble P is removed by extracting solution of 0.03 M NH_4F in 0.025 M HCl. Later phosphate-P in the extract is determined colorimetrically as phosphomolybdenum blue with ascorbic acid as the reducing agent and Sb added to give a stable Mo-P-Sb compound (Murphy and Riley 1962).

The exchangeable cations of Ca, Mg, K, and Na were determined by manual leaching method using vacuum extraction (Kalra and Maynard 1991). Since drying and storage process could cause a noticeable procedure-dependent reduction of cation exchange capacity (CEC) values (Meyer and Arp 1994) unbuffered NH_4Cl extracts was used and effective CEC was calculated from the sum of cation equivalents in the resulting extracts. The exchangeable cations in the NH_4Cl leachate were, then, determined by ICP-AES.

In this study, nutrients in the soil were expressed in both concentration (Mg g^{-1}) and content per area (kg ha^{-1} or ton ha^{-1}). The formulas used for conversion were illustrated in Appendix I. In each soil pit there were generally three horizons of H, A, and B, except the cases where organic matter alone or associated with either A or B are the only horizons above the bedrock. If the soil profile consisted of more than three horizons the minor ones were averaged and presented as one major horizon (Appendix I). For instance, if Bhf and Bf occurred together, the data from both were proportionally averaged and was presented as one major B horizon to maintain the sample size.

The dependent variable used in chapter 3 was site index of three species; sugar maple, American beech, and red oak. Site index ($BHSI_{50}$) is defined as the height, in metres, of dominant or dominant and co-dominant trees at 50 years breast-height age. All other recorded and measured variables in the field and laboratory were considered as independent variables. The list of variables and their abbreviations is illustrated in Appendix II.

CHAPTER 2. SOIL CHARACTERISTICS IN CENTRAL ONTARIO

2.1. INTRODUCTION

Tree species use a variety of mechanisms to exploit and alter their surrounding soil which are poorly understood. The competition for resources may improve soil nutrition by increasing the nutrient availability, exploiting nutrients at different times of the season or depths in the soil, and/or increasing nutrient recycling (Rothe and Binkley 2001). On the other hand, species such as sugar maple are able to modify soil chemical properties like acidity and available Ca content in surface soil (Dijkstra and Smits 2002) which may or may not benefit other species in a mixed forest. Tree species may also respond differently to soil chemistry alteration due to anthropogenic factors that can alter future forest composition.

The exploitation of nutrients at different levels can be a basis for species segregation. The spatial separation of plants according to soil factors may be described based on optimal performances of each species along nutrient gradients (Whittaker 1975; Finzi *et al.* 1998; Bigelow and Canham 2002). However, results from these studies are not conclusive but in some cases, *e.g.*, the segregation of dominant canopy trees in the northern hardwood forest along soil gradients, evidence is strong (Bigelow and Canham 2002).

Sugar maple, American beech, and red oak exist in mixedwood forests and are found occasionally as dominant trees in central Ontario. In spite of numerous studies regarding to the effects of soil nutrition on each of these species (Coté *et al.* 1995, Long *et al.* 1997, Demchik and Sharpe 2000, Horsley *et al.* 2002, Lovett and Mitchell 2004) and nutritional interaction in mixed species forests (Hix 1988, Smith 1995, Dijkstra and Smits 2001, Rothe and Binkley 2001, Bigelow and Canham 2002, Lovett *et al.* 2002), the nutritional interaction among these three species and the competitive mechanisms for nutrient exploitation in central Ontario are not well understood. As a result, this information is essential for predicting future forest function and composition as well as sustainable forest management.

The objectives of this chapter are: 1) to measure physical and chemical characteristics of soil under sugar maple, American beech, and red oak stands in tolerant hardwood forest in Ontario, and 2) to compare those soil characteristics among study species.

2.2. LITERATURE REVIEW

2.2.1. Sugar Maple

Sugar maple or hard maple is one of the largest and most important species in the hardwood forests of northeastern and midwestern United States and eastern Canada (Burns and Honkala 1990, Horsley *et al.* 2002). Mature trees, at 200 years old, may reach up to 35 m height and 90 cm diameter at breast height (DBH) (Farrar 1995). Sugar maple can tolerate heavy shade and browsing for several years and then grows after being released. Sugar maple is one of the most valuable timber species in northern hardwood forest and used for furniture, flooring, plywood, and veneer (Farrar 1995; Lovett and Mitchell 2004). The sap of sugar maple also has economic value with maple syrup industry, generating approximately $100 million annually in revenue from the northeastern U.S. and Canada (Allen *et al.* 1995).

2.2.1.1. Habitat

Sugar maple is a common broadleaf species in northern hardwood forests and found frequently in association with beech, yellow birch, black cherry, white ash, basswood and hemlock. Within Canada, sugar maple occurs from the southeast corner of Manitoba, through central Ontario, to the southern of Quebec and all of New Brunswick and Nova Scotia (Burns and Honkala 1990). In the Lake States, sugar maple is found at elevations up to 490 m; most commonly on ridges and on soil with at least 1 to 1.5 m to the water table (Burns and Honkala 1990). For the northern boundaries of sugar maple in central Ontario, the mean annual temperature reaches 0 to 4°C and the mean growing season length is 171 to 200 days (Hills 1959; Mackey *et al.* 1996; OMNR 1998).

2.2.1.2. Soil

Sugar maple grows best on deep, fertile, well-drained soils, with some lime content, although it also performs well on deep, non-calcareous soils of the Canadian shields (Farrar 1995). In the White Mountains of New Hampshire, sugar maple is abundant on fine tills with a sandy loam or finer texture with the presence of surface rocks and on enriched sites where the distinguishing feature is organic matter or organic-coated fine material incorporated into the mineral horizons (Leak 1977). In central Ontario, sugar maple is most productive on sandy loam, loamy sands, and silt loams (OMNR 1998). Sugar maple is sensitive to both drought and excessive soil moisture and like red oak and beech, sugar maple is most productive on fresh to moist sites in central Ontario (Hills 1959; Westing 1966; Ward *et al.* 1966). Sugar maple tolerates pH ranging from 3.7 to 7.3 but it usually grows on calcareous soils with a pH from 5.5 to 7.3 (Fowells 1965).

Studies suggest that acid deposition indirectly increases sugar maple decline by acceleration of long term base cation (Ca, Mg, K) loss in soils (McLaughlin *et al.* 1985; Long *et al.* 1997; McLaughlin and Wimmer 1999; Horsley *et al.* 2002). Similarly, Environment Canada (1990) suggested that the cation deficiency might be one of the reasons for sugar maple decline in the region, however, the results were not conclusive and more studies are needed to understand the mechanism of nutrients in the soils under hardwood forests of central Ontario.

2.2.1.3. Site quality assessment

The average height at age 50 for sugar maple ranges between 12 to 28 m, but, its growth pattern tends to be slower after age 50 in eastern regions (Carmean 1978; Burns and Honkala 1990). Foresters in central Ontario use modified site indices produced by Carmean (1978) in northern Wisconsin and Upper Michigan to predict growth and yield of sugar maple even-aged stands. In addition, a provisional site form diagram and table has been developed for uneven-aged sugar maple stands in Ontario. Further testing of this method is, however, needed for classifying potential sugar maple productivity in Ontario tolerant hardwood stands managed with partial harvesting systems (OMNR. 1998).

"Ecosite Productivity Classes by Soil Types" have, also, been developed for sugar maple for some soil types based on forest ecosystem classification (FEC) plot data (Chambers *et al.* 1997) where soil types of S3 (dry to moderately fresh moisture regime, coarse loamy, medium loamy, or silty texture and 1-24 cm depth of organic matter) and S6 (fresh to very fresh moisture regime and fine sandy texture with 2-22 cm depth of organic matter) have medium to high productivity. Productivity was estimated based on an evaluation of Site Forms in uneven-aged stands and was classified into high, medium, and low classes, which can be used to estimate the yield for managed and unmanaged stands (OMNR. 1998). The latter method gives an estimate of site quality of sugar maple stands. However, it is unable to provide a high level of accuracy of the estimation, nor does it have the ability to explain factors responsible for site productivity. These two issues were addressed in this study.

2.2.2. American Beech

American beech is the only member of *Fagaceae* family native to North America. It is a very shade tolerant, slow-growing hardwood that may attain ages over 300 years with heights up to 20 m and 100 cm diameter at breast height (DBH). Its wood is used for flooring, furniture, and woodenware and is especially favoured for fuelwood; also, its nuts are eaten by people and important food for wild life (Burns and Honkala 1990; Farrar 1995).

2.2.2.1. Habitat

American beech commonly occurs in association with sugar maple, yellow birch, basswood, black cherry, and oaks. In Canada, American beech occurs from Cape Breton Island, Nova Scotia to southern Quebec, and to southern Ontario. American beech is usually found in habitats where the mean annual temperature ranges from 4°C to 21°C and annual precipitation ranges between 760 mm to 1270 mm. However in central Ontario, American beech occurs in areas having greater than 635 mm of annual precipitation. The growing season for beech varies from 100 to 280 days (Burns and Honkala 1990; OMNR 1998). In central Ontario, it occasionally forms pure stands; but most often it is found in uneven-aged mixtures with sugar maple, yellow birch and hemlock (OMNR. 1998).

2.2.2.2. Soil

American beech grows best on fertile, moist, well-drained fresh soils, especially loamy soils with high humus incorporation (Farrar 1995). American beech can also be found on sandy to fine loamy and clay soils. Soils of high fertility are capable of producing beech that will yield high-quality lumber, veneer, or other special products. The presence of moisture throughout the summer is necessary for the development of beech (Hamilton 1955). Unlike sugar maple, productive stands of beech tend to occur on more acidic soils with pH ranging from 4.1 to 6.0 (Fowells 1965), but seldom where pH exceeds 7.0.

2.2.2.3. Site quality assessment

Site index of beech used by foresters in Ontario, ranges between 6 to 18 m at the base age 50, which was estimated by Carmean (1978) in the Lake states of the U.S. The rate of growth for this shade tolerant tree, unlike sugar maple, is constant before and after age 50. The "Ecosite Productivity Classes by Soil Types" has been developed for beech based on limited data in even-aged stands and its high productivity was found in soil types of S5 (fresh to very fresh moisture regime and coarse or medium sandy texture with 3-26 cm depth of organic matter) and S6 (fresh to very fresh moisture regime and fine sandy texture with 2-22 cm depth of organic matter). The knowledge about the soil characteristics and soil-site relationships of American beech in central Ontario is rare, and is reported in Chapters 2 and 3.

2.2.3. Red Oak

Red oak or Northern red oak is the common oak of eastern Canada ranging from east of Lake Superior to Nova Scotia. Mature trees at 150 years old are 20 to 30 m in height and 30 to 90 cm diameter at breast height (DBH). Red oak is less shade tolerant than its associates such as sugar maple and beech but more tolerant than black cherry and white ash. Red oak wood is strong and durable and is known as a high quality wood in furniture and flooring industries. In addition, red oak acorns are an important food resource for wildlife (Burns and Honkala 1990; Farrar 1995).

2.2.3.1. Habitat

Red oak is widespread in eastern Canada and grows on variety of soils and topography and often occurs as pure stands or mixed stands associated with other species such as sugar maple, basswood, and beech. Red oak occurs from east of Lake Superior to Nova Scotia (Farrar 1995). In central Ontario, red oak occurs in areas with mean annual temperatures above 4°C and mean annual precipitation ranging from 500 to 1500 mm (OMNR. 1998).

2.2.3.2. Soil

Red oak can occupy dry sites, but its best growth occurs on fresh-to-moist, well-drained soils in coves and mid/lower slopes (Sander 1957). At its northern limit, red oak may form pure stands on rocky ridge crests. In central Ontario, red oak highest coverage percentage is on fresh to dry, rich to moderately fertile ecosites. Most productive sites are characterized by fresh, loamy soils with soil moisture regimes between 2 to 4. However, red oak tends to reproduce more frequently on drier and coarser-textured (SMR 0 to 1) soils. Red oak is found on all topographic positions, but lower and middle slopes with northerly or easterly aspects, coves and deep ravines, and well -drained valley floors are optimal sites (Burns and Honkala 1990).

2.2.3.3. Site quality assessment

The modified site index of red oak produced by Carmean (1978) in Northern Wisconsin and Upper Michigan is used by foresters in central Ontario and it ranges between 12 and 24 m at the base age of 50 years (OMNR 1998). Also its "Ecosite Productivity Classes" have been assessed in central Ontario and soil types of S1 (with dry to moderately fresh soil moisture regime, coarse or medium sandy texture, and 1-14 cm depth of organic matter), S3 (with dry to moderately fresh moisture regime, coarse loamy, medium loamy, or silty texture and 1-24 cm depth of organic matter), and S6 (with fresh to very fresh soil moisture regime, fine sandy texture and 2-22 cm depth of organic matter) have medium to high productivity (OMNR 1998). The most productive red oak sites are found on lower concave slopes with thicker A horizon and loam to silt loam texture (Burns and Honkala 1990).

2.3. RESEARCH METHOD

2.3.1. Data Collection

All process regarding to study area, plot establishment, data collection and laboratory analysis are as the same as it was described in Section 1.3.

2.3.5. Statistical Analysis

SYSTAT® 10 and Excel 97 were used to conduct statistical analyse and data management. The statistical procedure included first, Canonical Discriminant Analysis (CDA) and, then, one-way analysis of variance (ANOVA).

CDA was carried out to identify those measured soil characteristics which contributed to the greatest degree of separation among study species. To do so, each group of variables including physical characteristics, nutrient pools, and nutrient concentration were tested separately to find those with better ability to separate species. Then, other variables from other groups were added, one by one, to enhance the separation. Also, automatic forward, backward, and interactive stepping of CDA were tested to reach the best combination of variables. The standardized coefficients of canonical discrimination can be viewed as weighting factors indicating the relative importance of each variable in separating the groups (Morris and Parker 1992).

A series of one-way analysis of variance (ANOVA) was carried out to determine those variables, independent from each other, which significantly varied among species. In ANOVA, models were checked for two basic assumptions of homogeneity and normality (Lorenzen and Anderson 1993). Testing for homogeneity was done using Bartlett's test, whereas normality was examined using scatter plots. When there was a large departure from either homogeneity or normality, the data were transformed.

2.4. RESULTS

2.4.1. Comparison of Soil Properties among Study Areas

Overall, 29 variables were included in canonical discriminant analysis in which 92 percent of the cases were classified correctly (Figure 2.1). Two forest units, namely Algonquin Park (AP) and the Haliburton Forest (HF) were close to each other; with the North Bay area (NB) showing more distinction particularly along the first axis. The nutrient concentrations produced better discrimination among the forest units when compared to the pool of nutrients (Table 2.1). Also, the pH of H and B horizons, in addition to physical characteristics of the soil such as the thickness of H and A, the coarse fragment of A and B, and silt content of A, were important discriminating variables.

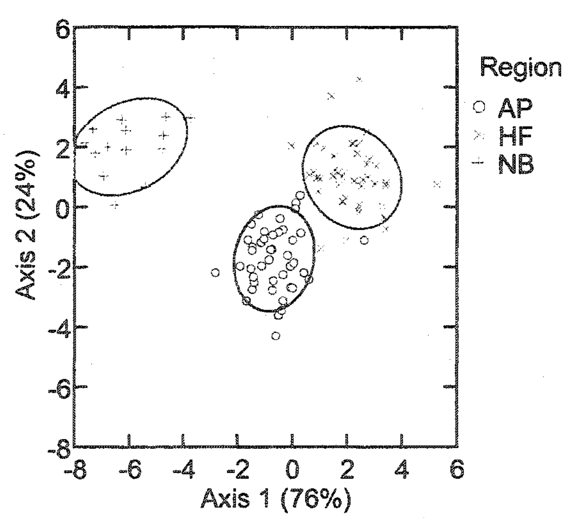

Figure 2.1. Canonical scores plot to discriminate three forest units. Areas included Algonquin Park (AP); Haliburton Forest (HF); and North Bay area (NB). Variables in the discriminate function were nutrient concentration and pH of all three horizons in addition to depth, thickness and soil volume of the H and A horizons, and coarse fragment of the A and B horizon.

Although, 76% of the variability was explained by the first axis, none of the variables, alone, was significantly important. In the first canonical function, where the separation between North Bay from the other two forest units occurred, Mg concentration in the H horizon, C and Na concentration in the A, and K concentration in the B horizon had absolute coefficient value larger than 0.5. On the other hand, the second axis, where Algonquin Park was mainly separated from North Bay and Haliburton, Mg concentration

Table 2.1. Standard canonical functions for three study region of Algonquin Park; Haliburton Forest; and North Bay area.

Variable[1]	Standardized canonical functions coefficient		Variable[1]	Standardized canonical functions coefficient	
	Canonical function 1	Canonical function 2		Canonical function 1	Canonical function 2
HpHc[2]	-0.106	-0.358	BNcon	0.299	0.044
BpHw[2]	0.013	1.044	BPcon	-0.102	-0.941
HPcon	-0.000	0.745	BMgcon	0.182	2.222
HMgcon	0.551	0.260	BCacon	-0.096	-2.296
HCacon	-0.018	-0.898	BNacon	0.369	-0.703
HNacon	0.462	0.275	BKcon	-0.503	-0.339
HKcon	-0.417	-0.660	Depth	-0.197	0.483
ACcon	-0.745	0.294	Hthick	-0.511	-0.746
ANcon	0.689	0.048	Hweight	0.634	0.537
APcon	-0.261	-0.052	Athick	0.574	-2.087
AMgcon	-0.059	-1.845	ACF	-0.571	0.144
ACacon	-0.129	1.564	Asilt	-0.229	-0.613
ANacon	0.646	0.342	Aweight	-0.362	2.170
AKcon	0.059	0.483	BCF	0.712	0.273
BCcon	-0.007	0.341			

[1] Variables abbreviations were defined in Appendix II.
[2] pH values were converted to $[H^+]$ concentration prior to analysis.

in the A and B horizons and Ca concentration and pH of the B horizon had absolute values of their respective coefficients greater than 1 (Table 2.1). Also, thickness and coarse fragment content of the A horizon, along with the coarse fragment content of the B horizon proved to be important factors on the second axis. Although, the thickness and soil volume of the A horizon were significant at the second axis, it must be noted that both variables were correlated to each other.

2.4.2. Comparison of Soil Properties among Species

Twenty seven variables were used for CDA to separate species and 54 percent of the cases were classified correctly. Red oak was discriminated from sugar maple and beech mainly on the first axis, while, beech and sugar maple separation occurred on the second axis (Figure 2.2). It should be noted that beech and sugar maple overlapped considerably, suggesting that they were commonly associated with each other in the

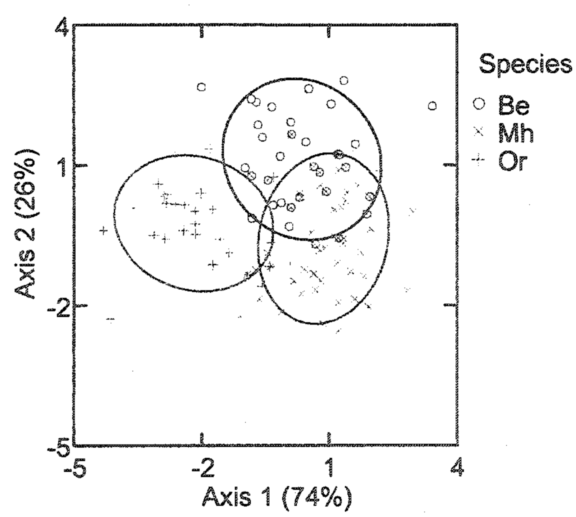

Figure 2.2. Canonical scores plot to discriminate the study species. Species included sugar maple (Mh); American beech (Be); and red oak (Or). Variables were pool of nutrients, pH, and C/N ratio of all three horizons in addition to depth, thickness, soil volume, coarse fragment, and sand and silt content of each horizon.

mixedwood stands, whereas red oak occurred more likely in the pure stands.

Important variables included in the first canonical function were pH, C, and N concentration in the B horizon with absolute values of their coefficients greater than 1 in separating red oak stands from other species followed by depth and soil volume of the B horizon with coefficients of 0.974 and -0.816, respectively (Table 2.2). Along the second axis, where to a large extent beech was separated from sugar maple, the thickness and

Table 2.2. Standard canonical functions for three study species of American beech, sugar maple, and red oak.

Variable[1]	Standardized canonical functions coefficient		Variable[1]	Standardized canonical functions coefficient	
	Canonical function 1	Canonical function 2		Canonical function 1	Canonical function 2
BpHc[2]	-1.005	0.298	BNcon	1.312	0.635
HCN	-0.327	0.336	BMgcon	-0.711	0.171
ACN	-0.355	0.237	BCacon	0.301	0.027
BCN	0.610	0.381	BNacon	0.332	-0.103
HCcon	-0.132	-0.365	Depth	0.974	0.126
HNcon	0.010	0.655	Hthick	0.033	-1.496
HPcon	-0.070	-0.736	Hweight	-0.104	1.597
HMgcon	-0.106	0.520	ADb	-0.011	-0.836
APcon	0.583	-0.013	Aweight	-0.100	0.349
AMgcon	-0.055	-0.345	Bweight	-0.816	-0.459
ACacon	0.698	-0.400	Bthick	0.198	0.509
ANacon	-0.114	0.391	BCF	-0.239	-0.283
AKcon	-0.718	0.614	BDb	0.347	0.893
BCcon	-1.465	-0.632			

[1] Variables abbreviations were defined in Appendix II.
[2] pH values were converted to $[H^+]$ concentration prior to analysis.

soil volume of the H horizon with coefficient of -1.496 and 1.597, respectively, were the most important factors followed by P concentration of the H horizon and bulk density of the B horizon.

2.4.2.1. Soil properties in the H horizons

All measured independent variables from H horizon were included separately, using a series of one-way ANOVA. Elevation and depth in addition to C:N ratio, pool of N, P, Na, and concentration of P and Na from H horizon were significantly different (*P<0.05*) among species (Table 2.3).

Table 2.3. Variables from H horizon with significant *p*-value (*P<0.05*) in one-way ANOVA.

Variable[1]	*p*-value	Variable[1]	*p*-value
Elevation	0.002	HP	0.012
Depth*	0.005	HNa	0.002
HCN*	0.010	HPcon	0.012
HN	0.026	HNacon	0.031

[1] Variable abbreviations were defined in Appendix II.
* Variable in common with canonical discriminant functions.

The beech stands were located at higher elevation (463.9 m) comparing to sugar maple and red oak stands at 399.4 and 354.0 m respectively (Figure 2.3.A). However, since the sample sites were selected arbitrarily, that may not be conclusive. The depth of rooting system under red oak stands (30.0 cm) was significantly shallower than that under either sugar maple (38.8 cm) or beech stands (36.2 cm) (Figure 2.3.B).

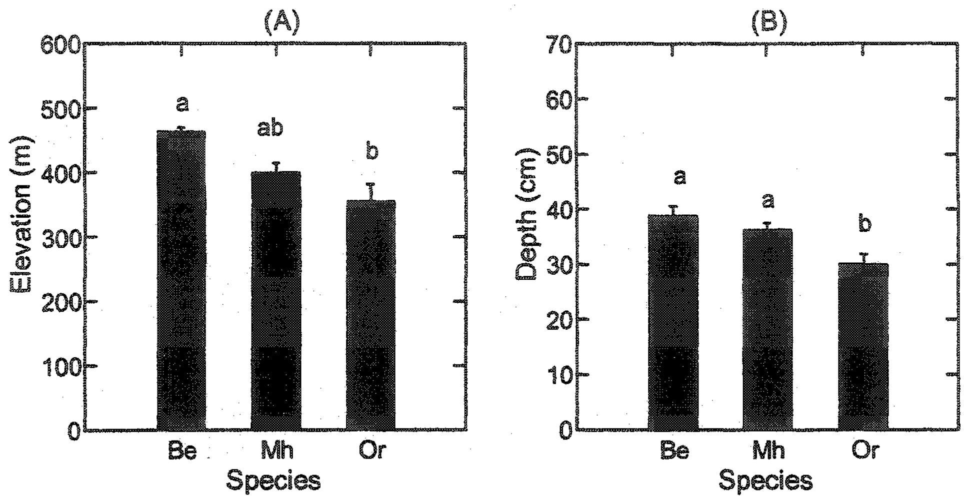

Figure 2.3. Distribution of elevations of sample plots where each stand located (A) and depth of soil profile under each species (B). Data illustrated for beech (Be), sugar maple (Mh), and red oak (Or) stands. Bars represent standard error of means. Values with the same subscript are not significantly different.

In terms of nutrients, the H horizon contained the same amount of N under red oak and sugar maple with 1058.10 and 966.52 kg ha^{-1} respectively, while under beech stands, there was 1439.35 kg ha^{-1} which was significantly higher (Figure 2.4A). On the

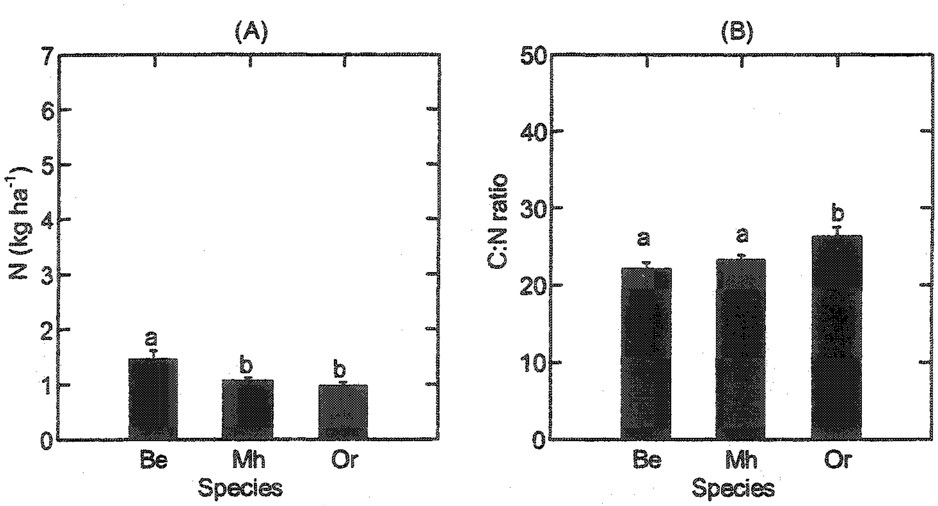

Figure 2.4. Distribution of N volume and C:N ratio in the H horizon. Data illustrated for beech (Be), sugar maple (Mh), and red oak (Or) stands. Bars represent standard error of means. Values with the same subscript are not significantly different.

other hand, red oak stands had higher level of C:N ratio (26.3) compared to beech and sugar maple with 22.1 and 23.3 respectively (Figure 2.4B).

Two elements, P and Na were different among species in terms of both concentration and pool size. Although the pool size of P under sugar maple (10.5 kg ha^{-1}) was not statistically different from others, H horizons under red oak stands had 12.6 kg ha^{-1} which was significantly higher than that under beech stands with 8.37 kg ha^{-1} (Figure 2.5A).

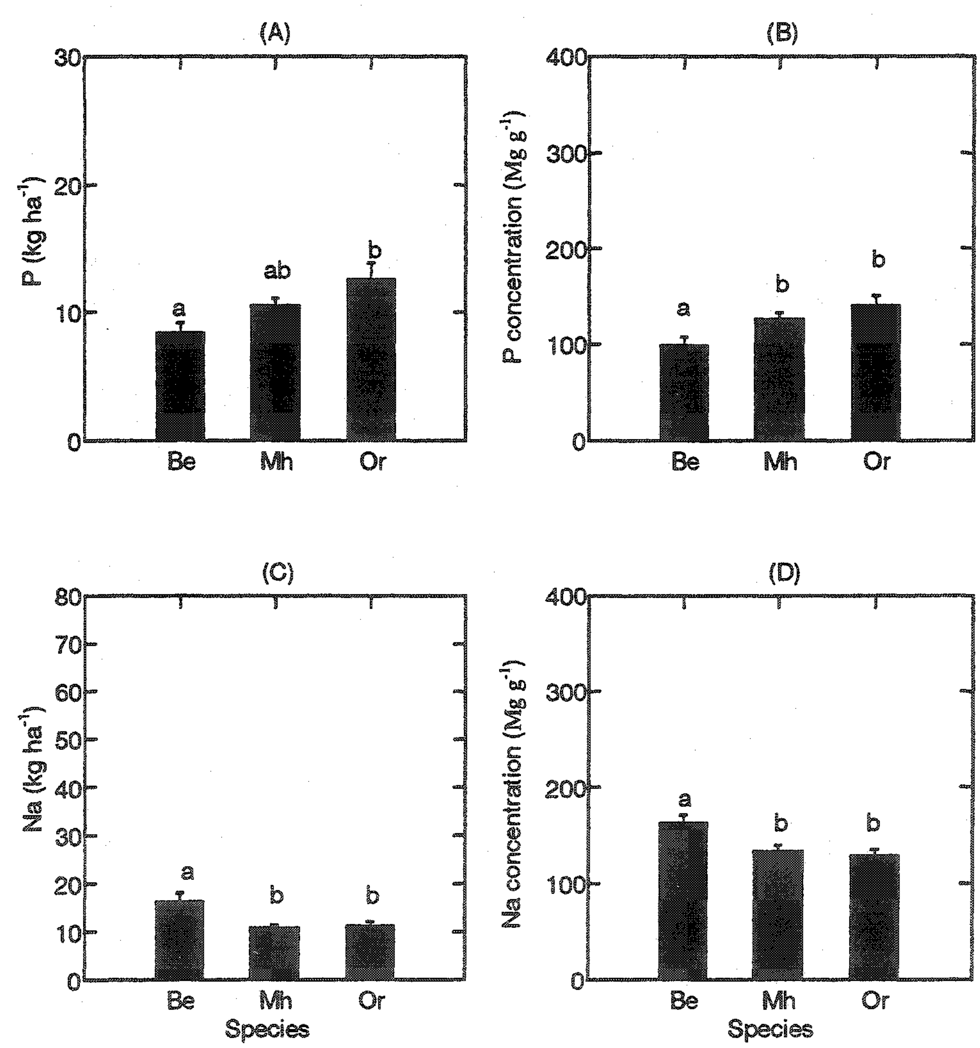

Figure 2.5. Pool size and concentration of P and Na in H horizon. Data illustrated for beech (Be), sugar maple (Mh), and red oak (Or) stands. Bars represent standard error of means. Values with the same subscript are not significantly different.

P concentration under sugar maple and red oak stands (126.32 and 139.24 Mg g^{-1}, respectively) were significantly higher than that under beech stands with 98.46 Mg g^{-1} (Figure 2.5B). On the other hand, more Na content was found under beech stands (14.61 kg ha^{-1}), than that under sugar maple and red oak with 10.81 and 11.21 kg ha^{-1}, respectively (Figure 2.5C). The same pattern was also found for the Na concentration (Figure 2.5D).

2.4.2.2. Soil properties in the A horizons

When comparing the physical and chemical properties of the A horizon, the thickness, pH of saturated soil in distilled water and $CaCl_2$, C:N ratio, pool of N, P, Mg, Ca, Na, and the concentration of P and Na were significantly different among species (Table 2.4).

Table 2.4. Variables from A horizon with significant *p*-value ($P<0.05$) in one-way ANOVA.

Variable[1]	*p*-value	Variable	*p*-value
Athick	0.003	AMg	0.010
ApHw[2]	0.005	ACa	0.000
ApHc	0.012	ANa	0.000
ACN*	0.002	APcon*	0.001
AN	0.017	ANacon*	0.034
AP	0.000		

[1] Variables abbreviations were defined in Appendix II.
[2] pH values were converted to $[H^+]$ concentration prior to analysis.
* Variable in common with canonical discriminant functions.

The thickness was the only physical characteristic of the A horizon that showed a significant difference among the study species. The average thickness of the A horizon under beech stands was 6.2 cm which was significantly thicker than that under sugar maple and red oak stands, which were 4.8 and 4.1 cm, respectively (Figure 2.6).

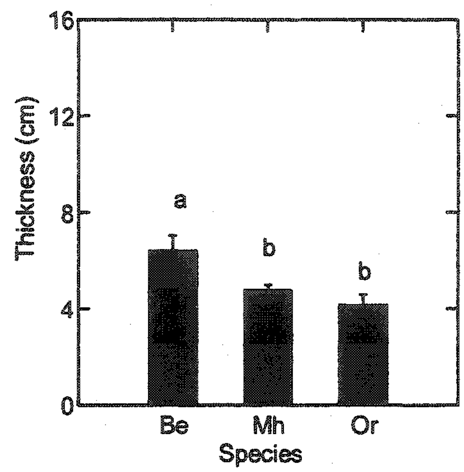

Figure 2.6. Distribution of thickness in the A horizon. Data illustrated for beech (Be), sugar maple (Mh), and red oak (Or) stands. Bars represent standard error of means. Values with the same subscript are not significantly different.

The pH of saturated soil in distilled water under red oak stands (4.20) was lower than that under beech and sugar maple which averaged 4.55 and 4.59, respectively. As might be expected, the same pattern existed for pH of saturated soil in $CaCl_2$ (Figure 2.7A and B). The pool of N under beech stands (1430.23 kg ha^{-1}) was higher than that under red oak and sugar maple with 958.2 and 1109.43 kg ha^{-1}, respectively (Figure2.7.C). Also, the C:N ratio (24.34) under red oak stands was higher than that under beech and sugar maple (20.58 and 20.21, respectively) (Figure 2.7D).

The beech and sugar maple stands had the higher amounts of P in the A horizon with 14.1 and 17.04 kg ha^{-1}, respectively, than that under red oak stands with 8.76 kg ha^{-1} (Figure 2.8A). The P concentration under sugar maple (51.09 Mg g^{-1}), also, was the highest level among beech and red oak stands with 36.06 and 37.95 Mg g^{-1} respectively

(Figure 2.8B). The pool of Na decreased significantly from beech to sugar maple and then red oak stands with 61.14, 43.97, and 27.01 kg ha^{-1}, respectively (Figure 2.8C). The concentration of this cation, also, was at higher level in beech stands with 138.61 Mg g^{-1}, but, no significant difference was found between sugar maple and red oak with

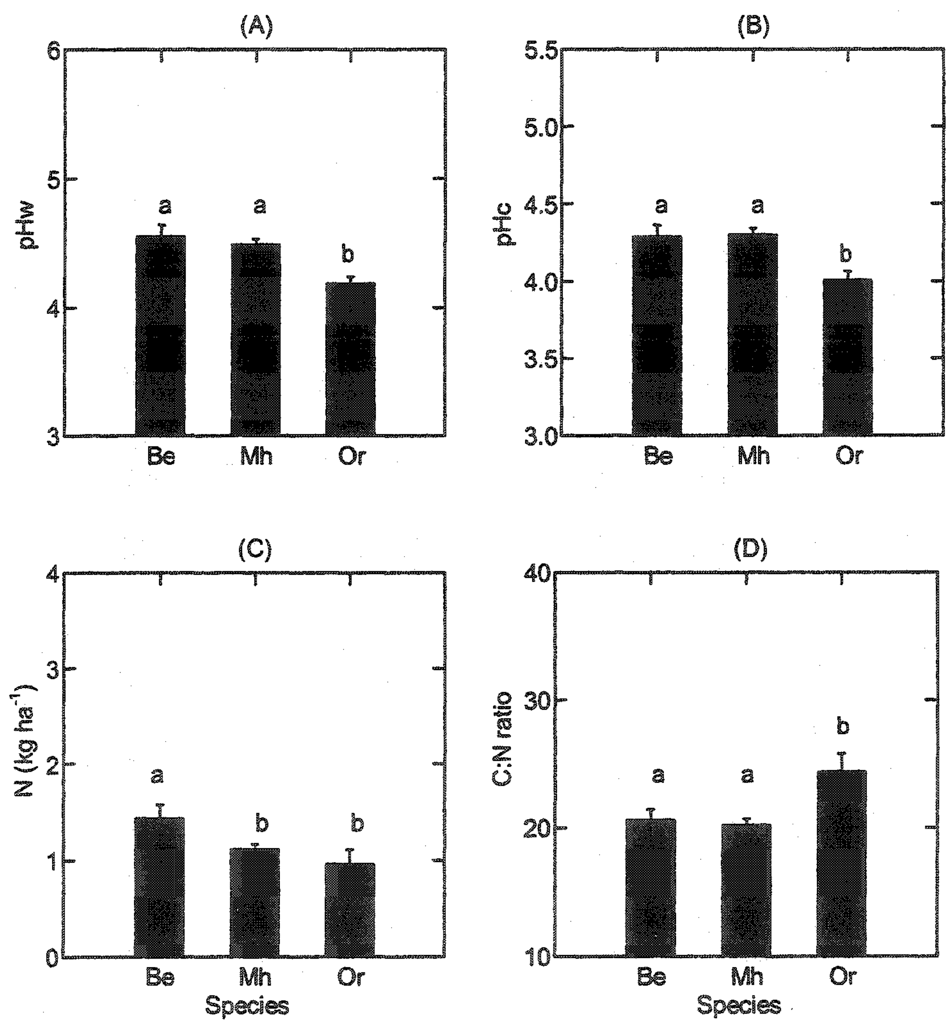

Figure 2.7. pH of soil in distilled water and $CaCl_2$, pool of N and C:N ratio in the A horizon. Data illustrated for beech (Be), sugar maple (Mh), and red oak (Or) stands. Bars represent standard error of means. Values with the same subscript are not significantly different.

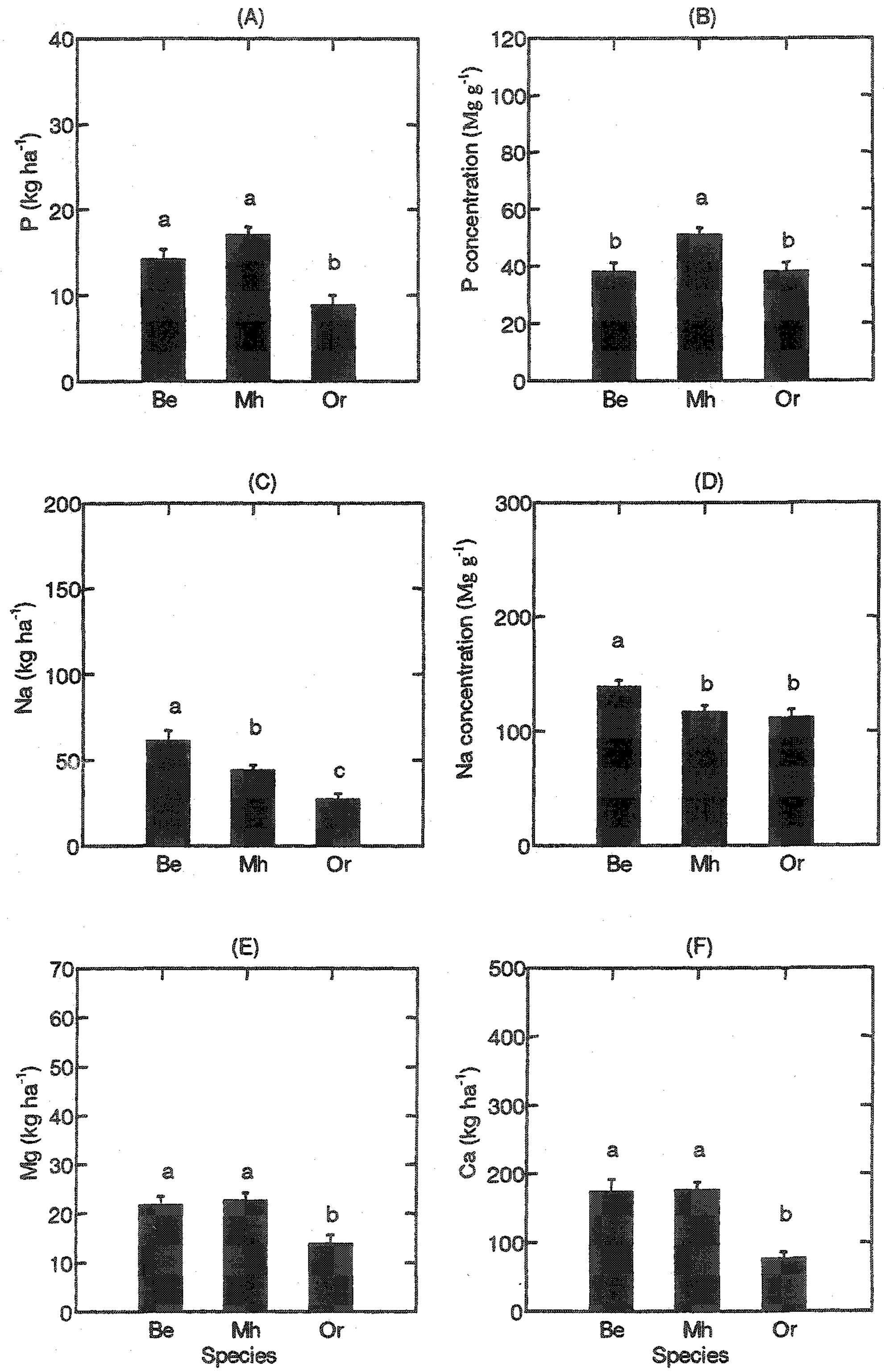

Figure 2.8. Pool size of P, Na, Mg, Ca, and the concentration of P and Na in the A horizon. Data illustrated for beech (Be), sugar maple (Mh), and red oak (Or) stands. Bars represented standard error of means. Values with the same subscript are not significantly different.

116.64 and 111.25 Mg g^{-1}, respectively (Figure 2.8D). The other measured cations, namely Mg and Ca, were lowest under red oak stands at 13.75 and 76.39 kg ha^{-1}, respectively, compared to beech and sugar maple stands (Figure 2.8E and F).

2.4.2.3. Soil properties in the B horizons

The percentage of sand and silt, the pH of saturated soil in water and $CaCl_2$, the pool of Ca, and the concentration of P, Ca, and Na, in B horizon (Table 2.5) differed across the study species.

Table 2.5. Variables from the B horizon with significant *p*-value (*P<0.05*) in one-way ANOVA.

Variable[1]	*p*-value	Variable	*p*-value
Bsand	0.004	BCa	0.003
Bsilt	0.006	BPcon	0.041
BpHw[2]	0.000	BCacon*	0.001
BpHc*	0.009	BNacon*	0.008

[1] Variables abbreviations were defined in Appendix II.
[2] pH values were converted to $[H^+]$ concentration prior to analysis.
* Variable in common with canonical discriminant functions.

The sand and silt contents were the only measured physical characteristics in the B horizon which significantly differed across the study species. While, both beech and sugar maple had the same amount of sand (69.56 and 69.12 percent, respectively) and silt (28.57 and 29.1 percent respectively), red oak stands had significantly higher amount of sand with 76.15 percent and lower amount of silt with 22.3 percent (Figure 2.9.A and B).

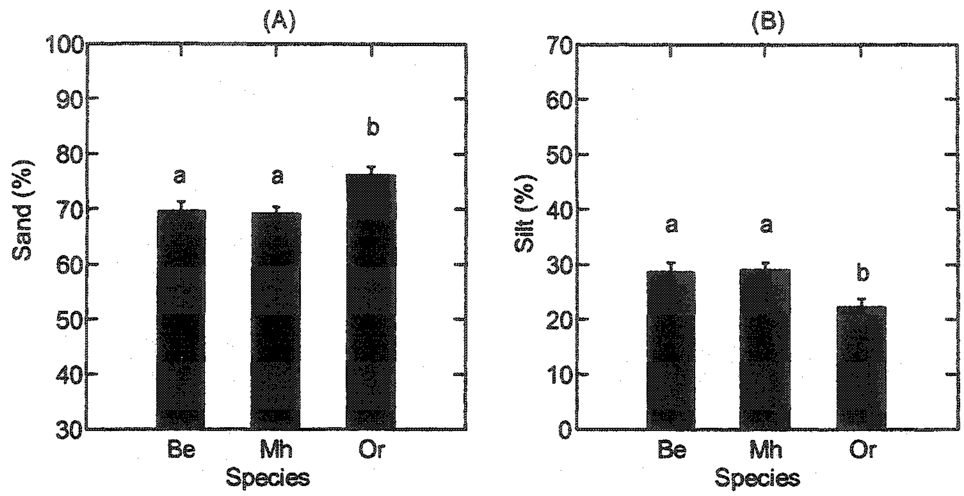

Figure 2.9. Sand and silt content (%) in the B horizon. Data illustrated for beech (Be), sugar maple (Mh), and red oak (Or) stands. Bars represent standard error of means. Values with the same subscript are not significantly different.

Both pH saturated in distilled water and $CaCl_2$ under red oak stands (4.78 and 4.38, respectively) were lower than those under beech stands (pH_{H2O} = 5.06; pH_{CaCl2} = 4.55) (Figure 2.10A and B). Sugar maple with pH value of 4.96 (pH_{H2O}) and 4.41 (pH_{CaCl2}) showed no significant differences from others. The amount of Ca in both pool size and concentration was significantly lower under red oak stands (Figure 2.10C and D). The pool size of Ca under sugar maple, beech, and red oak was 321.09, 285.56, and 151.55 kg ha^{-1}, and the concentration was 146.41, 136.31, and 73.69 Mg g^{-1}, respectively. The Na concentration under beech stands was, also, higher (127.8 Mg g^{-1}) than that under red oak stands with 91.36 Mg g^{-1}. In this case, however, sugar maple stands had less Na concentration (105.2 Mg g^{-1}) than beech and were similar to red oak (Figure 2.10E).

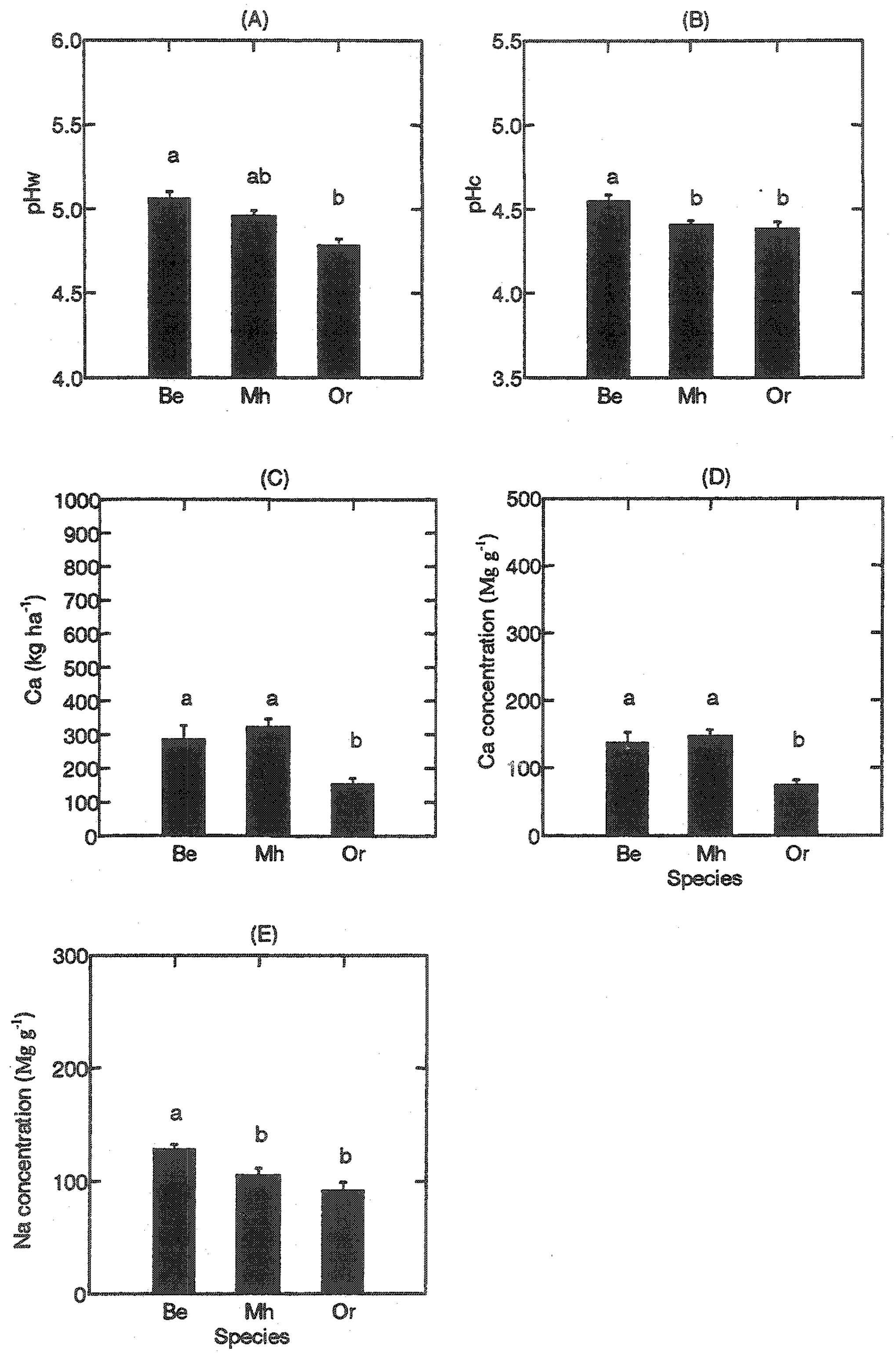

Figure 2.10. pH of soil in distilled water and $CaCl_2$, volume of Ca and concentration of Ca, and Na in the B horizon. Data illustrated for beech (Be), sugar maple (Mh), and red oak (Or) stands. Bars represent standard error of means. Values with the same subscript are not significantly different.

2.5. DISCUSSION AND CONCLUSION

Significant differences of the soil property distributions were mainly found between beech and red oak, while, sugar maple seemed to be more closely associated with beech. Under beech stands pool of N, and both pool and concentration of Na in the A and H horizons, pool of Mg and Ca in the A horizon, and both pool and concentration of Ca and concentration of Na in the B horizon were at the highest levels. In addition, the pH of soil saturated in both distilled water and $CaCl_2$ in the A and B horizons under beech stands were at the highest compared to red oak stands. Phosphorus was an exception, which was highest in the H horizon under red oak stands and in the A horizon under sugar maple stands.

Beech generally occurred at the lower end of P concentration gradient in the H, A and B horizons. Beech, also, showed a negative growth response to increasing P suggesting that its growth was optimal at lower levels of P. On the other hand, sugar maple being at the upper ends of P concentration gradient in the H, A, and B horizons did actually respond negatively with respect to growth. The negative correlation between P and site qualities of beech and sugar maple, despite the fact that P availability declines below pH 6.5 (Brady 1990), was surprising and showed that the increasing P in the soil could somehow stagnate their growths. It must be noted that P contents measured in this study contained largely calcium phosphates and some aluminium and iron phosphates (Kalra and Maynard 1991) which the latter ones are less available to plants. Accordingly, the increase of P in the soil might indicate the decrease of availability and eventual deficiency of this element to trees which degrade the site quality. This might not be conclusive unless more studies test the availability of this element to trees.

As a general rule, sugar maple and red oak occurred on soils with lower N values in either the H or A horizon compared to beech. However in the H and A horizons, both sugar maple and beech had slightly ($p<0.05$) lower C:N ratio compared to red oak stands. Most of the soil N is in organic form and associated with humus and silicate clay which is not available for plants (Brady 1990). Accordingly, the lower amount of N might be due to the higher rate of nitrification and ultimately decreasing the amount of organic form of nitrogen in the soil under sugar maple stands which is consistent with the findings of Verchot *et al.* (2001). Moreover, since the foliage litter of sugar maple has low lignin concentration, leading to higher litter decomposition rate (Pastor and Post 1986), the soil organic matter developed under sugar maple stands tends to have lower C:N ratios (Lovett and Mitchell 2004). On the other hand, red oak known as a species with lower net nitrification rate (Lovett and Mitchell 2004) had the same total N in the H and A horizons as sugar maple did. This similarity might be due to the sugar maple ability to alter the N contents of upper layers of soil (Lovett and Mitchell 2004) at sites shared with red oak stands. Neither beech nor red oak showed any response to N content increase of topsoil with respect to site quality.

Both beech and sugar maple occurred at higher levels of Ca and Mg contents in the A horizon and Ca in the B horizon, while, only red oak responded negatively to Ca concentration in the B horizon with respect to site quality. In terms of Na, both sugar maple and red oak unlike beech occurred on soils with lower Na concentration in the H, A, and B horizons. However, their growths responded differently to Na. While the site quality of sugar maple generally improved by increasing Na in the H and B horizons, red oak had a negative impact from higher levels of that nutrient in the B horizon. Previous studies showed that site quality of sugar maple responded positively to the enhancement of Ca and Mg availability at the upper layers of soil by adding fertilizer (Coté *et al.* 1995; Long *et al.* 1997; van Breeman *et al.* 1997; Finzi *et al.* 1998; Bigelow and Canham 2002; Horsley *et al.* 2002), while, beech seemed not to be responsive to those cations (Horsley *et al.* 2002). Red oak, on the other hand, was at the lower end of Ca gradient in the A and B horizons and Mg in the A horizon. The Ca concentration in the B horizon had, indeed, negative influence on the growth of red oak stands which was inconsistent with other studies in south western Pennsylvania (Demchik and Sharpe 2000) suggesting that the enhancement of cations (Ca, Mg, and K) in the A and B horizons, as a result of liming and fertilization, did increase the basal area growth of red oak. In contrary, red oak was more likely to be found on sites with lower Ca and Mg concentration in the B horizon.

In terms of physical characteristics, red oak stands tended to occur on shallower soil with more sand and less silt content in the B horizon comparing to both beech and sugar maple stands. In addition, red oak stands tended to have the shallower A horizons. Although deeper soils represent favourable conditions for all three species (Burns and Honkala 1990), it might be that the red oak was restricted to the shallower sites as the result of competition with more shade tolerant hardwoods such as sugar maple and beech. Furthermore, the higher content of sand in the shallower soil profiles, situated under the red oak stands, could facilitate the movement of water, gas, and nutrients and improve the regeneration chance for this species.

In this study, beech unlike red oak occurred on soils with higher N contents in the H and A horizons, Ca in the mineral soils and Na in all horizons. It also occurred on soils with lower P in the H horizon and sand content in the B horizon with less acidic mineral soils. Sugar maple, on the other hand, was similar to beech in terms of C:N ratio in the H and A horizons, CA and Mg contents in the mineral soil and texture of the B horizon. It also, occurred on soils with higher P in the mineral horizons.

CHAPTER 3. SOIL-SITE INDEX RELATIONS OF SUGAR MAPLE, RED OAK, AND BEECH STANDS IN CENTRAL ONTARIO

3.1. INTRODUCTION

One of the criteria of Ontario's framework for sustainable forest management is "...providing a continued and predictable flow of economic and social benefits from Ontario's forests" (OMNR 2002). Knowledge of potential growth and yield is a key element in managing deciduous forests of central Ontario. This provides reliable tools for foresters to examine the effects of different silvicultural methods on stands and the ability to estimate the volume production to maintain the sustainability of the forest management over the long term. This growth and yield information will also enable forest managers to concentrate the most intensive silvicultural activities of timber management on the most productive lands. Accordingly, identification and classification of forest lands based on their productivity would be a first and vital step toward the establishment and maintaining of healthy and fully-stocked stands with more valuable and productive forest tree species (Carmean 1996).

Site quality is the integration of soil (chemical, physical, biological), climate, topography and vegetation, which influences the composition and growth patterns of individual species and forest communities. The understanding of interrelationships among factors effecting site quality, thus, is a core requirement when attempting to predict the growth and yield responses of different tree species and stands over a given landscape (Vanclay 1994).

Site quality evaluation is a complex task because, as noted above, numerous factors affect plant growth. To better understand the growth of trees in relation to their environment, a host of site factors must be observed as a whole, not individually, particularly when site quality is indirectly evaluated (e.g., by using soil factors). Considering all elements contributing to site quality, however, is not practical. In addition, other factors such as irregular stocking, insect and disease, wildlife, and climate change can all influence the realized production versus the predictions.

Foresters have looked for reasonable and practical methods to evaluate site quality. Estimating site index from forest trees continues to be the most accepted direct method for estimating site quality in North America (Carmean 1975; Carmean 1996; Spurr and Barnes 1980; Pritchett and Fisher 1987) and Europe (Hägglund 1981). The site index method employs a routine procedure that measures the height of dominant trees at a predetermined age (e.g., 50 years for short-lived species; 100 years for long-lived species in the west coast). However, the application of this method requires the presence of free-growing trees which are not always available at the site. Moreover, a long history of selective harvesting combined by natural or man-made disturbances in an area might make trees unreliable indicators of site quality evaluation. In addition, in cases when the purpose of site quality evaluation is to introduce new species to a site, the direct methods do not work. Hence, "... foresters have placed their hopes for accurate prediction upon other indicators such as soil and topographic features" (Broadfoot 1969).

Abiotic factors such as soil, topography, and climate shape the environment around plants and often are associated with site quality. They are relatively stable through time and their combined influences determine directly or indirectly the nutrients, water flow other conditions which favour or limit the growth of plants (Carmean 1996; and Knoepp *et al.* 2000). The soil-site evaluation method has attracted more attention than other indirect methods for site quality evaluation in the United States (Carmean 1975) and Canada (Burger 1972).

In spite of the importance of the deciduous forests of central Ontario, foresters have had to use site quality applications developed in other regions; provinces and states to predict site indices of hardwood species. Site index curves of sugar maple, beech, and red oak in northern Wisconsin and Upper Michigan developed by Carmean (1978) and site classes of sugar maple and beech developed by Plonski (1974) for Ontario are currently used (OMNR 1998). Currently there is not a soil-site index model that has been developed for these species in Ontario.

Therefore, the objectives of this chapter of the study were: 1) to determine the correlation between site indices of each target species and a suite of soil and site variables, and 2) to develop models by using those variables with stronger correlations to predict site-index values.

3.2. LITERATURE REVIEW

3.2.1. History of Site Quality Evaluation

The concept of site quality evaluation of forest land has its origin from agriculture. There are some references, dating back to ancient European and Asian civilizations that report on the productivity of lands and soils as they were used for crop production (Warkentin, 1995). The recognition that forests can only generate a limited wood supply, although considered as a renewable resource, and as they represent important economical value, eventually, forced foresters and researchers to develop methods to measure the biomass produced by trees and classify the forested lands based on their productivity.

During the 18th and 19th centuries, forests in Europe were subjectively classified from rich to poor sites (Hartig 1795, and Cotta 1804). Baur (1876) in Germany chose stand volume as an indicator of site quality. He measured stand volume of Norway spruce (*Picea abies* (L.) Karst.) of different ages and produced harmonized graphs. In the late 19th and early 20th century, the classification of forests based on stand volume became the standard method in Germany. Later, Bates (1918) suggested using "...current volume increment of a fully stocked stand of the species under consideration" as an indicator of site quality. The volume yield of a defined area of even-aged stands, adopted from Europe, was accepted as the best method for site quality evaluation by the "Society of American Foresters" in 1916 but it was not accepted as the standard method (Sparhawk *et al.* 1923). The following year, Watson (1917) arose with questions regarding the ability of this method to classify forest sites in America. Growth declines resulting from natural events, such as windfall, insect attacks, as he mentioned, might affect two sites with the same quality and both could produce different volume yields. He also claimed that this method could not be applied in uneven aged and mixed wood forests where every combination of ages and species were possible. Moreover, this method had practical obstacles which made it difficult to be used (Carmean 1976).

"Forest site types", introduced by Cajander (1926) and based on understory vegetation, was another method adopted for site evaluation. This method has been used widely in northern Europe and Canada particularly for coniferous forests where two or three understory species are dominant on sites of a particular quality. In hardwood forests, however, this method is less applicable as many understory species occur over a wide range of site quality. It is also difficult to be used in recently disturbed forests or forests having great contrasts in composition and stocking (Carmean 1975).

Although height measurement as an indicator of site quality had already become a standard method for site quality evaluation in Europe since the mid-19th century, Watson (1917) and Frothingham (1918) were the first ones in North America who used height as an index of site quality (Vincent 1961). Spurr (1952) did criticize this method, although he did refer to it as the best measure of site, but not a perfect one. While some studies raised doubts about the accuracy of this method, it was strongly supported by Roth (1916, 1918), Watson (1917), Frothingham (1918, 1921), and Sterrett (1921).

Ker (1952) concluded that the use of heights of dominant trees only is satisfactory in immature Douglas-fir. Lorenz and Spaeth (1947) showed that the growth pattern of eastern white pine, Scotch pine, Europe larch, and Norway spruce plantations on prairie soils of Illinois changed with age. Rowe (1953) also found that white spruce plantations had different patterns of growth at different sites. Furthermore, different age classes may have different growth patterns. These problems were encountered when the conventional method of harmonic growth curves were used. These shortcomings, however, were overcome in the 1970's when polymorphic techniques were developed and used to estimate site index. Afterwards, site index based on height growth is now the most acceptable direct method for estimating site quality (Carmean 1975; Spurr and Barnes 1980; Carmean 1996).

3.2.2. Site Quality Evaluation Methods

There are two fundamental approaches to site quality evaluation:

1) direct method; measurement of vegetative characteristics which are considered to be sensitive to changes of site quality,

2) indirect method; measurement of site factors that are closely associated with tree growth.

3.2.2.1. Direct methods

Theoretically, one stand of a certain species and age on a given site will produce the same amount of wood per year at different stocking level if the site is fully occupied (Barnes *et al.* 1998). Accordingly, site index can be directly estimated from forest trees if 1) the stand is undisturbed, even-aged, fully-stocked, and 2) sample trees are free growing, uninjured dominant and/or co-dominant (Carmean 1975). One must bear in mind that site index is an indication of relative productivity of a stand of one species comparing to the productivity of the same species at other sites, but, it does not indicate which factors are really responsible for that level of quality (Barnes *et al.* 1998). Here, five different direct methods are mentioned.

3.2.2.1.1. Site index curves

Site index estimation, measured directly from forest trees, is the most common way used to estimate site quality across North America (Carmean 1975; Carmean *et al.* 1989; Spurr and Barnes 1980; Pritchett and Fisher 1987) and Europe (Hägglund 1981). For most eastern forest species, site index is defined as the mean height of dominant or dominant and co-dominant trees at 50 years total age or breast height age. Depending on nature of the species, the index age may be older, e.g. 100 years for long-lived species on west coast or younger, e.g. 30 for short-lived species, or plantations with shorter rotations (Carmean *et al.* 1989; Barnes *et al.* 1998).

This method is simple to use as long as suitable site trees are available. Such a condition usually occurs in even-aged, fully stocked stands with no recent history of natural or man made disturbances. The average height of dominant trees can be later used in related tables to predict growth and yield volume of the stand. Also, they show the potential productivity of the stands.

The basic assumption involved with this technique is that the stand density has no significant influence on the height-age relationship (Lorenz and Spaeth 1947; Vincent 1961). Although some studies have suggested significant correlation between site index and stand density (Parker 1942; Vincent 1954; Curtis and Reukema 1970; MacFarlane *et al.* 2000), these effects were more obvious in young stands and became less influential as stands reach maturity.

3.2.2.1.2. Growth intercepts

The growth intercept method is a direct method of site-quality estimation in which the total length of the first five internodes produced after breast height (Carmean 1975) is used to estimate growth potential. This method is most suitable for conifers such as white spruce and red pine which have distinct internodes marking annual height growth (Thrower 1986).

The growth intercept method is usually applied to younger stands, e.g. less than 20 years old, where using site index curves based on dominant tree height at 50 years are not possible. Other advantages of using growth intercepts are: 1) tree age measurements are not needed thus trees are not injured by increment borers; 2) errors associated with counting annual rings or measuring total tree height are avoided; 3) measuring internodes above breast height avoids errors due to slow and erratic height growth that occurs below breast height; and 4) growth intercepts can be quickly and easily measured (Carmean 1996).

3.2.2.1.3. Site-index comparisons between species

The site-index comparison method is used to compare and contrast the growth habits of different tree species on a particular site. In even-aged monoculture stands, site index of present species can be directly estimated, while, direct site-index estimation for other species is impossible because of the lack of suitable trees. In this method the site index of present species is used as a means for estimating site-index of other alternative species that could be considered for management on that particular site (Carmean 1996). Site index comparison graphs are obtained from sites where suitable trees for stem analysis and producing site indices for two or more species are present. Those graphs can be applied, later, at sites where some of species are absent. The average height of dominant trees at a certain age (site index) of different species may vary greatly across a wide site array, thus, site-index comparison method could have an unknown degree of inaccuracy. However, this method does provide estimate of growth potential for other species (Barnes *et al.* 1998).

3.2.2.1.4. Site form

Direct site quality evaluation using height at an index age is complex and impractical in uneven-aged stands. In the site form method, site quality is estimated based on height at a

selected index diameter of breast height and varies according to species (OMNR 1998). Strong correlations between site form and both basal area and periodic volume increment were found in some studies (Vanclay 1988). A provincial site form diagram and table has been developed for sugar maple in Ontario (OMNR 1998) and for sugar maple, red oak, beech and yellow birch, site forms have been developed on smaller scales based on central Ontario conditions (Buda 2004).

3.2.2.1.5. Site class

A generalized form of site quality classification is site class in which a range of site indices is divided into poor (Site Class 3); good (Site Class 2); better (Site Class 1); and best (Site Class 1a - for black spruce only) SI groupings. Classes were developed empirically by Plonski (1957) using anamorphic curves through individual height-age measurements for multiple plots per species (OMNR 1998). Despite the fact that the curves did not show the growth pattern at different ages, they are still used as a practical site quality assessment method in Ontario (OMNR 1998).

3.2.2.2. Indirect methods

In a situation where there is no suitable dominant and co-dominant trees or the desired species is not present on the site, the direct methods are not useful and indirect methods of site quality evaluation are considered as alternative methods. The basic assumption here is that site quality is the integration of soil, climate, topography and other factors, that ultimately, influence species composition and growth patterns (Vanclay 1994).

3.2.2.2.1. <u>Plant indicators</u>

The growth and abundance of free-growing trees and understory plants are the integration of environmental features of local forest ecosystems and thus they may be considered as site quality indicators (Carmean 1975; Barnes *et al.* 1998). The correlation, however, between plants and site quality may be affected by factors unrelated to site quality such as competition, grazing, insect and disease outbreaks, fire, or manmade disturbances. In addition, many species with wide ecological amplitudes occur on a wide variety of sites which make them less useful as indicators of site quality. Moreover, understory plants, due to their shallow rooting behaviour, are usually not good representatives of deeper layers of soil (Carmean 1975).

Generally in this method the area under study is stratified into sub areas based on physiographic and soil characteristics and then the understory vegetation is recognized and classified into vegetation communities and assigned to site index values (Carmean 1975). In addition, the site must have the minimum of disturbance so that the natural vegetative assemblages remain intact, thus, represent reliable indicators of site quality. This method will be discussed more in chapter 3.

3.2.2.2.2. Forest Ecosystem Classification (FEC)

FEC classification is based on the recognition of the effects of interactions of climate, landform and soils on the distribution of vegetation (Chambers *et al.* 1997). In central Ontario it allows any relatively undisturbed forest ecosystem to be classified to one of 25 ecosite types (with moisture classes), 41 vegetation types and 26 soil types (Chambers *et al.* 1997).

Site indices can, then, be related to ecosite types, vegetation types, and soil types. It must be noted that the broad and general forest-land classification units having wide variations in site index and, as such, can only be used for broad and general estimates of forest site quality and yield (Carmean 1996).

3.2.2.2.3. Soil site evaluation

Soil productivity is usually defined by foresters as the ability of a soil to produce biomass per unit area per unit time (Ford 1983). Three main functions of soil are: 1) to act as a medium for plant growth; 2) to regulate and partition water flow; and 3) to serve as an environmental buffer (Knoepp *et al.* 2000). These functions, integrated with climate, and vegetation, form the tree growing environment.

Site index can be indirectly estimated using soil-site methods based on research where site index is directly measured on a large number of plots representing the full range of site quality, soil and topography of a particular area or region (Carmean 1996). However, understanding the complex interrelationships between soil factors and site index is not a simple process. In general, those soil characteristics which influence the quality and quantity of growing space for tree roots have been found to be closely related to site quality (Coile 1952).

Depending on the microclimate and topography of a given study area, influential factors may prove to be different. For example, a study area having relatively level land would rarely have topographic features correlated with site index (Carmean 1996). Furthermore, some soil characteristics are closely associated with each other, thus an important independent variable may not only be strongly correlated to site quality, but may also be correlated to other variables.

In spite of difficulties in choosing the most related environmental and soil variables to site index among other measured variables, the evaluation of site quality from soil characteristics has some advantages. Firstly, soil condition is relatively stable over a long period of time. Secondly, site quality can be evaluated by soil factors in those areas where suitable trees or the desired species are not present. Finally, stand density or other vegetative factors tend to have little influence on soil characteristics.

3.2.2.3. History of soil-site evaluation

There has been a long history of soil-site work in agriculture. Information derived from agricultural site productivity research has raised questions about the possible similarities of soil-site relations in forest evaluation. The basic differences between agriculture and forestry made soil scientists believed that forest soils should be studied as an independent subject. Although Lutz and Chandler (1946) published the first comprehensive book dealing with forest soils in North America (Armson 1977), some early studies had already taken place. Hickock and his colleagues (1931), for example, had found a slight correlation between colloidal content and site index of young red pine (*Pinus resinsa* Soln.) plantations in Connecticut. They also reported that total nitrogen content of the A horizon had a positive correlation with site index.

Coile (1935) investigated the relationship between site index of shortleaf pine (*Pinus echinata* Mill.) and some physical properties of the soil. He concluded that the average depth of the surface soil and the amount of silt and clay in the subsoil were important parameters to consider when determining the site quality of that species. Turner (1938) found that those soil features which affected the available water such as slope, exposure, depth of soil, and physical structures of the soil horizons were important in determining plant growth.

Coile and his colleagues (1952) continued with similar studies, emphasizing that "... site quality is largely determined by soil properties, or other features of site which influence the quality and quantity of growing space for tree roots". Although they recognized the possible influence of soil nutrients on site index, they felt that the nutrient deficiency was usually not as limiting of a factor as physical properties and it would normally be reflected in various physical properties.

In the southern U.S., most of the site classification schemes for hardwoods were based on local topography and land forms (Putnam 1951 and Putnam *et al.* 1960). The failure of the early studies in that region to link soil properties to site index was the result of insufficient sample size and the inability to identify the true "drivers" of productivity (Broadfoot 1969). Broadfoot, however, pointed out that nutrients and soil moisture during the growing season, as well as soil aeration and root growing space, are important factors for growth of hardwood species in southern U.S.

In spite of early studies of soil-site relations, which focused on physical properties of soil, some other scientists focused on the chemical nature of soil. For example, Voigt *et al.* (1957) found that northern Minnesota soils with high levels of calcium, potassium, and nitrogen were more productive than soils with low levels of these nutrients. Ralston (1964) pointed out that the most important reason for lack of emphasis on fertility factors in studies of site productivity is the frequent correlation between variables used to describe other soil properties with nutrient supply. He also noted the difficulty in diagnosing the fertility status of forest soils. When other site factors are kept constant, soil nutrient levels are indeed related to site productivity (Pritchett and Fisher, 1987).

Earlier soil-site studies in U.S. have been reviewed by Coile (1948, 1952), Doolittle (1957), Della-Bianca and Olson (1961), Rennie (1963), Ralston (1964), Broadfoot (1969), and Carmean (1975, 1982). Many additional soil-site studies have been published for Canada (Burger, 1972).

The combination of soil properties and other ecological factors with site index have also become a topic for further studies in recent years. Since 1970's the relation of climatic and soil conditions with site indices of various species have been studied several times (Monserud 1984; Klinka et al. 1994; Chen et al. 1998b, 1998c; Fralish and Loucks 1975; Monserud *et al.* 1990; Klinka et al. 1994; Kayahara *et al.* 1995; Wang 1995, 1997; Wang and Klinka 1996; Chen *et al.* 2001). In several cases, it was found that the models using the combination of climatic variables and local soil conditions as predictors represent better models than those using only climate variables or local site factors if models were developed for a large geographic area (Chen *et al.* 2001). But on smaller scales, because of minor changes in climate, this factor becomes relatively constant throughout the studied area and tends to not be related to site quality.

3.2.2.4. Soil characteristics as indicators of site quality

It is often difficult to isolate individual soil characteristics due to the dynamic and interactive nature of those functions. However, it is necessary to identify those soil characteristics that have the most pronounced effect on site quality.

Soil texture, as the percentage of mineral soil particles from various sizes, largely determines the physical matrix of a soil profile, and, as such also determines nutrient circulation, water movement, and aeration. These functions directly and indirectly affect plant growth by influencing nutrient availability, root development, moisture regime, and gas exchange. However, the overall importance of soil texture on site quality can be confounded with other physiographic and climatic variables. For example, in the coastal plains of Southeast of U.S., changes in soil moisture conditions brought about by small differences in elevation may completely overshadow textural effects (Pritchett and Fisher, 1987).

Also, each soil particle class plays a different role in determining overall site quality. For example, the presence of coarse fragments facilitates the aeration in the soil while highly coarse sandy soils have little ability for moisture and nutrient retention. On the other hand, finer textured soils with higher percentage of silt and clay retain and provide more water and nutrients for plants (Brady 1990).

Parent material is a major factor in soil genesis which can have indirect effects on tree growth. Knowledge of the parent material of youthful soils is essential in understanding their properties and management. Due to glacial history of central Ontario, parent materials are geologically young, and the soils derived from them usually are not drastically leached. Young soils generally have higher available nutrients and under comparable conditions, are superior for crop production (Brady, 1990). As soil ages, the influence of parent material on its properties decreases (Pritchett and Fisher 1987). However, in areas like central Ontario with a glacial history, where the upper soil layers have been transported from other places the relationship between parent material and soil productivity may be more complex.

Soil depth is a quantitative characteristic of soil which influences directly the amount of nutrients available to plants. In addition to texture, soil thickness also plays an important role in water content and oxygen availability (Larson and Pierce 1991; Arshad and Coen 1992; Doran and Parkin 1994).

Soil acidity (pH), in combination with adsorption and exchange reaction, determines the nutrient availability as well as microbial activity (Pritchett and Fisher 1987, Barnes *et al.* 1998). Thus, it is logical that pH should be considered as a chemical indicator, especially when it is routinely included in soil surveys and is an easy and inexpensive measurement (Schoenholtz *et al.* 2000). It should be noted that soil pH may vary up to 1.0 unit due to seasonal changes. Also vegetation and parent material are among the other important elements influencing soil acidity. Accordingly, the timing, forest composition, and parent material must be in consideration when pH is used.

Nitrogen is an essential component of chlorophyll, as well as proteins which are necessary for plant growth. Nitrogen is mainly available to trees in soluble (inorganic) forms of either nitrate (NO_3^-) or ammonium (NH_4^+) ions. Phosphorous, although generally found at low concentration levels in forest soils, is also essential for plant growth. Cations including Mg^{2+}, Ca^{2+}, Na^{+}, and K^{+} are among the macronutrients important for plants. Their abundance and availability to plants have direct relationship with pH.

Soil organic matter or soil organic carbon is commonly recognized as one of the key factors of soil quality influencing both physical and chemical characteristics of soil (Schoenholtz *et al.* 2000). It influences the soil porosity, gas exchange and water retention. Organic carbon, also, has crucial role in nutritional cycling and availability *e.g.*, in nitrogen cycle (Johnson 1985; Brady 1990; Henderson 1995; Nambiar 1997).

3.3. RESEARCH METHOD

3.3.1. Data Collection

The process of data collection was as the same as described at Section 2.3. Site index values were obtained from Buda (2004) and subjectively grouped into good, medium, and poor sites (Table 3.1). For each species, attempts were made to have site quality classes with possibly equal sample size and range of site index values.

Table 3.1. Site quality classes of American beech (Be), sugar maple (Mh), and red oak (Or) and their appropriate site index value groups.

	Good		Medium		Poor	
Species	Range	Sample size	Range	Sample size	Range	Sample size
Be	13.5-17.5	15	10.5-13.5	12	7.5-10.5	12
Mh	16.5-20.5	30	12.5-16.5	30	8.5-12.5	30
Or	15.5-18.5	12	12.5-15.5	9	9.5-12.5	12

3.3.2. Study Plot Stratification

Simple regression analysis showed very low correlation coefficients (r) between site index and all of the independent variables for sugar maple. As a result, the sample plots of sugar maple were stratified into three study groups of Algonquin Park (AP), the Haliburton Forest (HF), and the North Bay area (NB) which resulted in better fitting models. This stratification was not done for the other two species since strong correlations between site index values and some independent variables were found.

Twenty percent of the sample plots from each study group were randomly selected to be used as verification plots. This procedure was not done for sugar maple stands from the North Bay area due to its small sample size.

3.3.3. Variable Definition and Computation

A total of 73 independent variables for each study species were defined (Appendix II). All variables were measured either in the field or analyzed in the laboratory as outlined previously in Section 2.3. Aspect and slope were categorical variables and were arbitrarily grouped and treated as discrete variables.

The coarse fragment content of the H horizon (HCF) was not used because of inaccurate measurement due to the existence of appreciable amount of debris and woody particles in the samples. Also, A horizons in some cases, were too thin to be sampled (less than 3 cm), thus, the average of A horizons of two other soil pits at the same plot was computed and used in place of the missing A horizon.

All variables met the following criteria before being used in the statistical analysis, described below:

1) they were available for each plot

2) they were independent from site disturbances

3) they had reasonable relationships with site quality

4) they could be obtained in the field or through a routine laboratory procedure (Schmidt and Carmean 1988).

3.3.2. Statistical Analysis

Canonical Discriminant Analysis (CDA) was used as a multivariate approach to identify those variables which were most likely responsible for the separation of the site quality classes for each of the study species. To do so, automatic forward, backward, and interactive stepping of CDA were tested to reach the best combination of variables. Also, three groups of variables including physical characteristics, nutrient pools, and nutrient concentrations of each horizon were first used separately to identify which group had a better ability to classify the samples into groups. Then the best candidates were selected and used together to build the best combination of variables. The standardized coefficients of canonical discrimination can be viewed as weighting factors indicating the relative importance of each variable in separating the groups (Morris and Parker 1992).

A series of simple linear regression analyses between site index and each independent variable was carried out. Those variables which had significant correlation with site index were selected for the regression analysis. A series of multiple regressions was carried out to achieve the best model. At each stage, those independent variables with the higher probability in the F-test were eliminated to narrow down the number of variables in the equations.

The presence of eigenvalues less than 0.01 and condition indices greater than 15 were considered as the presence of multicollinearity (SYSTAT 2000). To detect multicollinearity, the Variance Inflation Factors (VIFs) were calculated. VIF less than 10 indicated that the collinearity was not a problem (Chatterjee *et al.* 2000). Each independent variable was tested for normality by checking the scatter plot of the actual versus expected value. Finally, the linearity was detected by checking plots of each variable against site index. Four transformation methods including natural logarithm, reciprocal, square root, and quadratic were used wherever it was needed to improve the regression model.

As part of the regression analysis, the following assumptions were also tested:

1. All error terms belong to a population and thus there were no abnormal values. Bonferonni's t-test (Weisberg 1980) was used for detecting outliers.
2. The homoscedasticity assumption which implies that the errors have the same variance (Chatterjee *et al.* 2000). The scatter plots of residuals versus predicted values were studied for this assumption.

Those models which had higher coefficient of multiple regression (R^2) and lower probability (p value) and standard error of the estimate (SEE) were chosen as the final regression model.

3.4. RESULTS

3.4.1 Soil-Sit Relationships for Sugar Maple

Mean, maximum, minimum, and standard deviation of site index of sugar maple for each region were measured and illustrated in Table 3.2.

Table 3.2. Summary of site index values[1] of sugar maple stands. Data are from all three Forested areas (C), Algonquin Park (AP), Haliburton Forest (HF), and North Bay area (NB). Site index (SI_{BH50}) is total height of dominant and co-dominant trees at breast height age 50 years.

Region	No of soil pits	Minimum	Maximum	Mean	Standard deviation
AP	39	8.30	21.5	14.00	3.51
HF	30	12.10	21.75	16.06	2.82
NB	21	11.80	21.13	15.36	2.71
Combined	90	8.30	21.75	15.00	3.22

[1] Obtained from Buda (2004)

The pool and concentration of nutrients were tested for CDA separately, with the nutrient concentrations showing stronger relationships with the site quality classes compared to the nutrient pool data. Next, the physical characteristics were added to the nutrient concentration model in a stepwise fashion to find which variables improved the model more. The nutrient concentration, pH and C:N ratio of all three horizons, as well as the percentage of coarse fragment in the A and B horizons, and the thickness of the B horizon were used in CDA. The interactive stepping function was carried out to eliminate some of the variables which were redundant due to having correlations with other included variables. At the end, 19 out of the original thirty four variables were included in the discriminant function that reclassified 61 percent of the site index values into their correct quality classes (Figure 3.1). The standardized canonical function coefficients of the most important variables participating in site quality separation of sugar maple stands were summarized in Table 3.2.

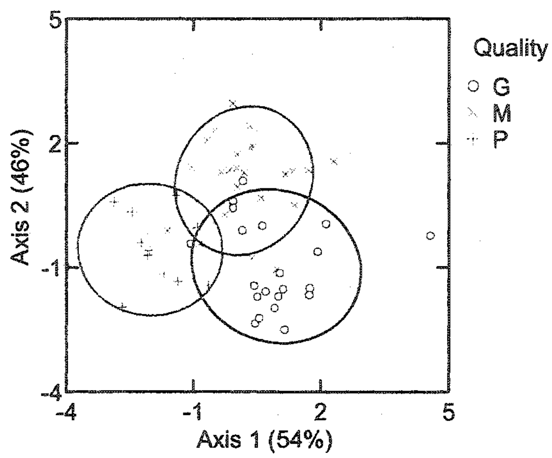

Figure 3.1. Canonical scores plot to discriminate site quality classes of sugar maple stands. Site quality groups included good (G); medium (M); and poor (P) sites and variables were nutrient concentration, pH, and C:N ratio of all three horizons in addition to coarse fragment and bulk density of the A horizons and the thickness and coarse fragment content of the B horizons.

Separation between good and poor sites occurred on the first canonical axis where pH of saturated soil in distilled water, N and K concentration and coarse fragment content of the A horizon and coarse fragment content of the B horizon had canonical function coefficient absolute values greater than 1. On the other hand, the medium sites, tended to separate out from other quality sites on the second axis where K concentration in the H horizon, and C and K concentrations in the A horizon as well as K concentration in the B horizon, had the greatest influence on separation (Table 3.3).

Table 3.3. Standard canonical functions for good, medium, and poor sites of sugar maple stands.

Variable[1]	Standardized canonical functions coefficient		Variable	Standardized canonical functions coefficient	
	Canonical function 1	Canonical function 2		Canonical function 1	Canonical function 2
HpHw[2]	0.570	0.057	ANcon	2.112	0.555
ApHw	-1.159	-0.860	AMgcon	-0.801	0.564
ApHc	0.333	0.724	AKcon	-1.187	-1.128
BpHw	1.190	-0.539	BPcon	-0.585	0.033
HCN	-0.329	0.317	BMgcon	0.633	0.758
ACN	0.769	-0.002	BCacon	-0.584	0.217
BCN	-0.390	0.469	BKcon	-0.360	-1.152
HNcon	-0.728	0.813	ACF	2.309	0.478
HMgcon	0.844	0.275	BCF	-1.746	-0.538
HKcon	-0.525	-1.407	Bthick	0.435	0.268
ACcon	-0.751	1.342			

[1] Variables abbreviations were defined in Appendix II.
[2] pH values were converted to $[H^+]$ concentration prior to analysis.

Among the nutrient variables, K concentration in the A horizon was dominant in both canonical functions, whereas N concentration in the A horizon had the largest coefficient (2.112) in the first function. Mg and K were the only nutrients whose concentrations influenced the site quality differentiation in all three horizons. Also, the pH of saturated soil in distilled water for all three horizons, but particularly from the A horizon, made a significant contribution to both canonical functions. The C:N ratio in the A horizon had an impact on site quality in the first function, whereas, the ratio in the B horizon was less influential and on exhibited an inverse relationship in both functions.

None of the measured physical variables proved to be important in the second canonical function, however, the coarse fragment of A and B horizons were significant in terms of site quality differentiation between good and poor sites. In addition to the thickness of B horizon, they were the most important physical variables among the data set.

3.4.1.1. Soil-site relationships for sugar maple in the Algonquin Park

A series of simple linear regression analysis was carried out between site index of sugar maple stands in Algonquin Park as dependent variables and each measured independent variable. Those with greater standard coefficient were summarized in Table 3.4.

Three variables including pH and C:N ratio of H and P concentration of the B horizon, also, were similar to those having the greatest influence on site quality classification from Table 3.3. Only two variables of content and concentration of P (BP and BPcon, respectively) had significantly linear relationships with site index of sugar maple in Algonquin Park. Interestingly, the soil volume of H and its associated nutrient pools, particularly those closely linked to organic matter content (e.g., C and N) had a negative relation with site index. In the B horizon, both P and C were also negatively correlated, whereas, Na was positively related to site index.

Table 3.4. Standard coefficient (SC), R^2, and the p-value of simple linear regression analysis between site index and independent variables of sugar maple stands from Algonquin Park.

Variable[1]	SC	R^2	p-value	Variable	SC	R^2	p-value
Hthick	-0.467	0.22	0.392	HN	-0.427	0.18	0.507
Hweight	-0.514	0.26	0.271	HNa	-0.515	0.27	0.625
Bweight	0.320	0.10	0.725	ACacon	-0.306	0.09	0.765
HpHw[2]*	0.411	0.17	0.129	BNa	0.387	0.15	0.898
HK	-0.386	0.15	0.641	BP	-0.406	0.16	0.015
HCN*	-0.316	0.10	0.071	BCcon	-0.356	0.13	0.265
HC	-0.441	0.19	0.237	BPcon*	-0.438	0.19	0.009

[1] Variables abbreviations were defined in Appendix II.
[2] pH values were converted to $[H^+]$ concentration prior to analysis.
* Variable in common with canonical discriminant functions.

Multiple linear regression analysis was carried out to develop models for predicting site index of sugar maple stands in the Algonquin Park. Five samples were dropped due to missing data, then, 7 soil pits were randomly selected as checking samples. First, those variables with higher coefficients in CDA (Table 3.3) were used to develop multiple regression models, of which, the best result was Equation 3.1 (Table 3.5).

The same process was done using variables with higher standard coefficients with site index (Table 3.4) to develop an alternative multiple regression model which resulted Equation 3.2. Results were nearly identical, with the only difference being the inclusion of P concentration in the B horizon. In the first model (Equation 3.1), the data were not transformed, however, the logarithm of the content of P in the B horizon was used in Equation 3.2.

Table 3.5. Summary of the best fit multiple regression equations for sugar maple from Algonquin Park utilizing the important variables from the CDA (Eq.3.1), and simple linear regression analysis (Eq.3.2).

	Regression Equation	N	R^2	R^2_{adj}	SEE	*p* value
Eq.3.1	SI = 2.684 + 4.592 (HpHw) - 0.271 (HCN) - 0.054 (BPcon)	27	0.419	0.354	3.023	0.002
Eq.3.2	SI = 9.540 + 4.679 (HpHw) - 0.260 (HCN) - 2.345 (log BP)	27	0.464	0.404	2.903	0.001

Where: SI = site index (m)
HpHw = pH of saturated soil of the H horizon in distilled water
HCN = C:N ratio of the H horizon
BPcon = P concentration in the B horizon (Mg g^{-1})
BP = pool of P in the B horizon (kg ha^{-1})

Both equations were used to estimate the site index of the verification data set (n = 7) with the results summarized in Table 3.6. The poorest estimate (plot 12, soil pit 1) was generated by the equation 3.1 with an error of 5.9 meters. The error was due to unusual

Table 3.6. Actual and predicted site indices of sugar maple stands for the verification data set (n=7) from Algonquin Park using equation Eq.3.1 and Eq.3.2.

Plot (soil pit)	SI Actual	SI predicted	Residual	SI predicted	Residual
		Eq.3.1		Eq.3.2	
1 (3)	14.7	13.6	1.0	13.0	1.7
5 (2)	16.8	17.1	-0.4	15.8	1.0
7 (2)	12.0	13.4	-1.5	13.2	-1.2
12 (1)	10.3	14.2	-5.9	11.3	-1.0
16 (2)	13.3	13.2	0.1	14.2	-0.9
20 (3)	10.4	10.5	-0.2	11.3	-0.9
21 (3)	15.6	16.2	-0.6	16.2	-0.6

low concentration of P (39.09 Mg g^{-1}) in the B horizon of the first soil pit of plot No. 12. The average concentration of P in other two soil pits was 72.84 Mg g^{-1}, therefore, that one was considered as an outlier and was dropped.

All 34 samples were used to develop the final equations which were illustrated in Table 3.7. All variables used in the equations were checked for normality. Also the scatter plots of residuals showed no indication of heteroscedasticity (Figure 3.2). Figure 3.3 showed the trend graph of predicted site index versus actual site index.

Table 3.7. Summary of the final multiple regression equations for sugar maple stands from the Algonquin Park utilizing the important variables from the CDA (E.q.3.3), and simple linear regression analysis (E.q.3.4).

Regression Equation		N	R^2	R^2_{adj}	SEE	*p* value
E.q.3.3	SI = 2.373 + 4.629 (HpHw) - 0.264 (HCN) - 0.055 (BPcon)	34	0.419	0.361	2.886	0.001
E.q.3.4	SI = 10.351 + 4.656 (HpHw) - 0.264 (HCN) - 2.508 (log BP)	34	0.508	0.457	2.677	0.000

Where: SI = site index (m)
HpHw = pH of saturated soil of the H horizon in distilled water
HCN = C:N ratio of the H horizon
BPcon = P concentration in the B horizon (Mg g^{-1})
BP = pool of P in the B horizon (kg ha^{-1})

Two models showed very close results in terms of scatter plots of residuals and predicted versus actual site index (Figure 3.2 and 3.3). In Equation 3.4, the estimation of log BP required extra measurements of bulk density, and coarse fragment content which not only would be more time consuming and expensive, it would also produce more error.

As a result, Equation 3.3 was chosen as the best model for site index determination of sugar maple in the Algonquin Park.

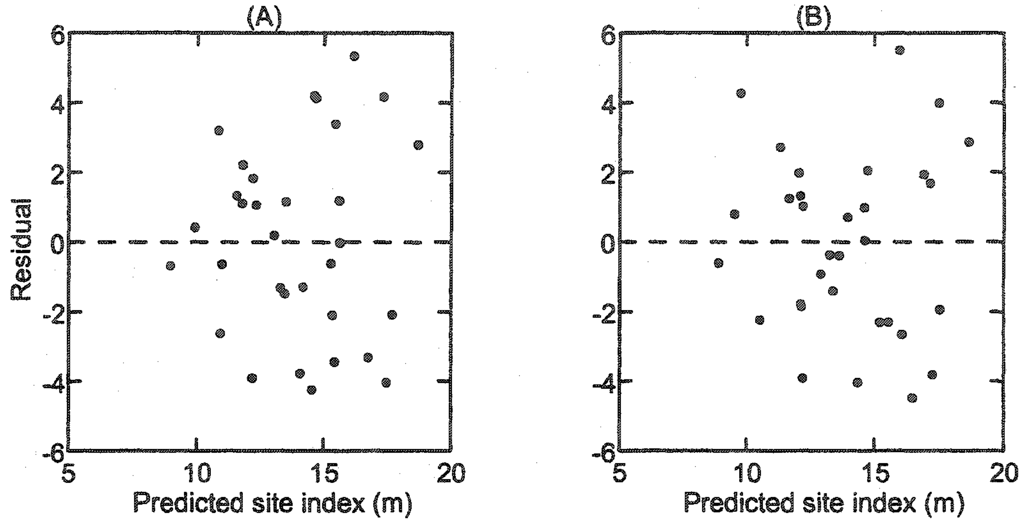

Figure 3.2. Scatter plots of residuals versus the predicted site indices of sugar maple stands from Algonquin Park. (A) Scatter plot of Eq. 3.3; (B) scatter plot of Eq. 3.4.

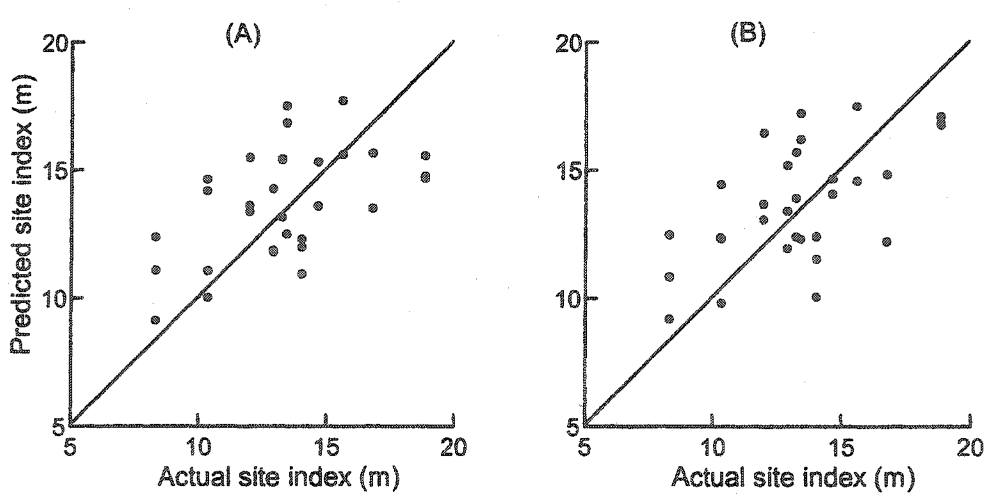

Figure 3.3. Predicted and measured site index values of sugar maple stands from Algonquin Park. (A) Scatter plot of Eq. 3.3; (B) scatter plot of Eq. 3.4. The solid lines were 1:1 ratio and representing perfect fit.

3.4.1.2. Soil-site relationships for sugar maple stands in the Haliburton Forest

Simple linear regressions were conducted between site indices and each independent variable (Table 3.8). Elevation had a strongly negative correlation with site index of sugar maple, however, the elevations of sample plots did not distribute normally and there was a gap between two plots at 300.00 and 325.00 m with the rest of the sample plots starting from 390.00 m. In terms of physical characteristics, coarse fragment and texture of the A and B horizons were significant. The coarse fragment content in A horizon was positively related with site index (0.708), whereas, in the B horizon, it exhibited a negative influence on site index (-0.632). It should be remembered that coarse fragment content, also, had an important role in site quality classification (Table 3.3). In both mineral horizons, sand content was positively and silt content negatively correlated with site index.

Table 3.8. Standard coefficient (SC), R^2, and the *p*-value of simple linear regression analysis between site index and independent variables of sugar maple stands from Haliburton Forest.

Variable[1]	SC	R^2	*p*-value	Variable	SC	R^2	*p*-value
Elevation	-0.862	0.74	0.000	HP	-0.404	0.16	0.069
ACF*	0.708	0.50	0.000	HNa	0.614	0.38	0.001
BCF*	0.632	0.40	0.005	HNcon*	-0.495	0.25	0.023
Asand	0.767	0.59	0.002	ApHc[2]*	-0.495	0.25	0.006
Asilt	-0.785	0.59	0.001	ACcon*	0.462	0.21	0.012
Bsand	0.511	0.26	0.025	BCper	0.379	0.14	0.051
Bsilt	-0.513	0.26	0.025	BNa	-0.364	0.13	0.062
HN	-0.441	0.19	0.045				

[1] Variables abbreviations were defined in Appendix II.
[2] pH values were converted to $[H^+]$ concentration prior to analysis.
* Variable in common with canonical discriminant functions.

In the H horizon, the pool size and concentration of N along with the pool size of P were negatively correlated with site index, whereas, the pool size of Na demonstrated a positive relationship. Further to this, in the B horizon, the pool size of Na was negatively and C concentration positively correlated with site index. C concentration in A horizon was also positively correlated with site index while higher pH values favoured sugar maple growth.

At this stage for multiple regression analysis, five samples were randomly selected as a 20% verification data set, with the remaining data used in the multiple regression analysis. Important variables in the CDA were used in the multiple regression analysis to produce Equation 3.5, which had the best fit (Table 3.9). By using variables with high standard coefficients (Table 3.7), an alternative regression equation was derived (Table 3.9: equation 3.6).

Table 3.9. Summary of the best fit multiple regression equations for sugar maple stands from the Haliburton Forest utilizing the important variables from the CDA (Eq.3.5), and simple linear regression analysis (Eq.3.6).

	Regression Equation	N	R^2	R^2_{adj}	SEE	*p* value
Eq.3.5	SI = 24.718 - 2.868 (ApHc) + 2.279 [log (BCF)]	21	0.588	0.537	1.606	0.001
Eq.3.6	SI = 10.812+ 0.192 (HNa) + 0.282 (BCcon)	21	0.676	0.642	1.063	0.000

Where: SI = site index (m)
ApHc = pH of saturated soil of the A horizon in $CaCl_2$
BCF = coarse fragment content in the B horizon (%)
HNa = pool of Na in the H horizon (kg ha^{-1})
BCcon = C concentration in the B horizon (%)

For validation, both equations were used to estimate site indices of the five sample trees in the validation data set. The results were summarized in Table 3.10. Generally, the residuals generated using Equation 3.5 were smaller than those generated by Equation 3.6.

Table 3.10. Actual and predicted site indices of sugar maple stands for the verification data set (n=5) from Haliburton Forest using both equation Eq.3.5 and Eq.3.6.

Plot (soil pit)	SI Actual	SI predicted	Residual	SI predicted	Residual
		Eq.3.5		Eq.3.6	
1 (1)	15.8	14.0	1.8	14.0	1.8
6 (2)	14.7	14.2	0.4	13.0	1.6
7 (3)	12.1	10.2	1.9	14.1	-2.0
14 (1)	14.3	16.1	-1.8	12.3	2.1
19 (1)	16.1	17.6	-1.5	17.3	-1.2

Again, all samples were used to generate the final equations and the results were illustrated in Table 3.11. The scatter plots of residuals versus predicted site index values for both equations were shown in Figure 3.4. Figure 3.5 also illustrates the predicted site indices versus actual site index values for both equations.

Equations 3.7 and 3.8 used different independent variables to predict site index of sugar maple in the Haliburton Forest. Although, all independent variables included in model development had normal distributions and the scatter plots of residuals for both models were the same, the performance was slightly different. The R^2 value for Equation

Table 3.11. Summary of the final multiple regression equations for sugar maple stands from the Haliburton forest utilizing the important variables from the CDA (Eq.3.7), and simple linear regression analysis (Eq.3.8).

	Regression Equation	N	R^2	R^2_{adj}	SEE	*p* value
Eq.3.7	SI = 24.472 - 2.876 (ApHc) + 2.450 [log(BCF)]	26	0.637	0.597	1.570	0.000
Eq.3.8	SI = 11.710 + 0.139 (HNa) + 0.247 (BCcon)	26	0.503	0.453	0.947	0.000

Where: SI = site index (m)
ApHc = pH of saturated soil of the A horizon in $CaCl_2$
BCF = coarse fragment content in the B horizon (%)
HNa = pool of Na in the H horizon (kg ha^{-1})
BCcon = C concentration in the B horizon (%)

3.7 (0.637) was larger than that of Equation 3.8 (0.503), whereas, the standard error in Equation 3.8 (0.947) was less than that in Equation 3.7 (1.570). In Equation 3.7, the pH of the A horizon is easily obtained using a simple lab procedure and the logarithm of the coarse fragment content in the B horizon obtained using a straightforward field procedure. In Eq.3.8, both independent variables (pool size of Na in the H horizon and C% in the B horizon) required more sophisticated lab procedure. The residuals of predicted versus actual site index values from Eq.3.7 tended to be smaller than those generated from Eq.3.8. Overall, Equation 3.7 seemed to be a better model to be used because of simpler soil analysis procedure compared to Equation 3.8.

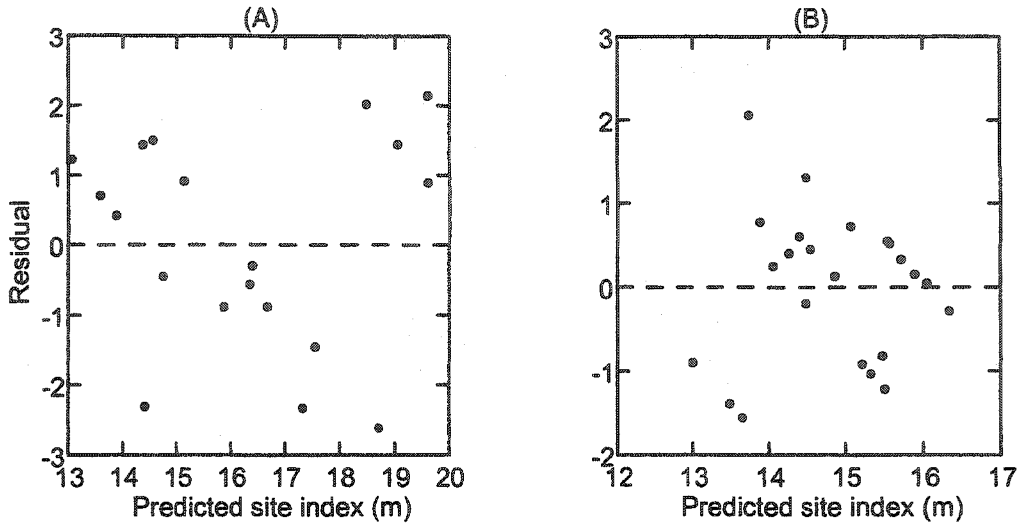

Figure 3.4. Scatter plots of residuals versus the predicted site indices of sugar maple stands from Haliburton Forest. (A) Scatter plot of Eq. 3.7; (B) scatter plot of Eq. 3.8.

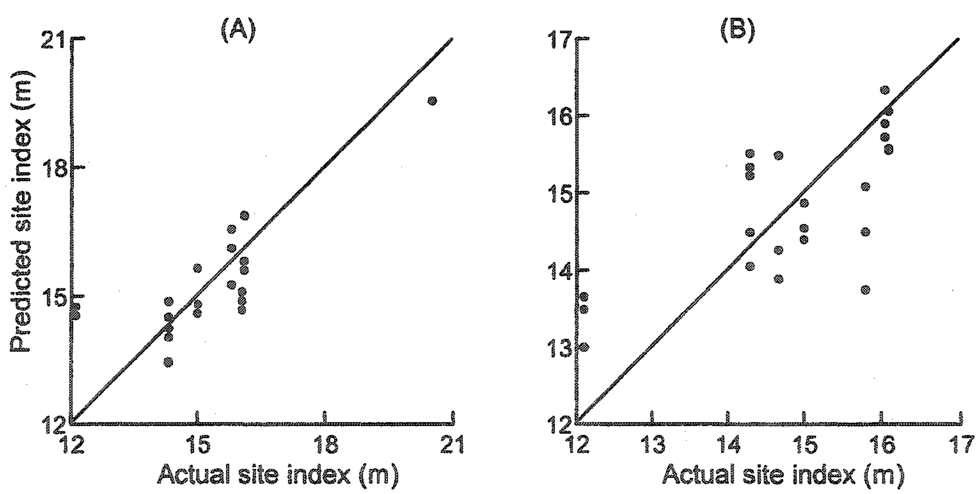

Figure 3.5. Predicted and measured site index values of sugar maple stands from the Haliburton Forest. (A) Scatter plot of Eq. 3.7; (B) scatter plot of Eq. 3.8.

3.4.1.2. Soil-Site Relationships for Sugar Maple in the North Bay area

In the same way, a series of simple linear regressions were carried out for sugar maple stands from the North Bay area. The variables which had significant correlation with site index were summarized in Table 3.12.

Texture and coarse fragment of the A and B horizons, as well as the nutrient pools in the H horizon had the strongest relationship with site quality. Coarse fragment content in both the A and B horizons had negative effects on site index along with silt content, while, sand content had a positive impact on sugar maple growth. N content in both pool size and concentration along with the pool size of P in the H horizon were negatively correlated with site index, whereas, Na concentration in the B horizon had a positive influence.

Table 3.12. Standard coefficient (SC), R^2, and the *p*-value of simple linear regression analysis between site index and independent variables of sugar maple stands from North Bay area.

Variable[1]	SC	R^2	*p*-value	Variable	SC	R^2	*p*-value
ACF*	-0.567	0.32	0.035	HpHc	0.431	0.20	0.051
Asand	0.767	0.59	0.002	HN	-0.441	0.19	0.045
Asilt	-0.785	0.62	0.001	HP	-0.404	0.16	0.069
BCF*	-0.632	0.40	0.005	HNcon*	-0.495	0.25	0.023
Bsand	0.511	0.26	0.025	BNacon	0.616	0.38	0.008
Bsilt	-0.513	0.26	0.025				

[1] Variables abbreviations were defined in Appendix II.
[2] pH values were converted to $[H^+]$ concentration prior to analysis.
* Variable in common with canonical discriminant functions.

In the case of the North Bay area, because of the small sample size, samples were not split into computation and validation data sets. Multiple regression analysis was carried out twice using important variables from the CDA (Table 3.3) and the simple regression results to develop models that explained the variation in site index. Two equations of Eq.3.9 and Eq.3.10 were developed and summarized in Table 3.13.

In Eq.3.9, two independent variables including the pH of saturated soil in CaCl2 solution of the H horizon (HpHc) and the logarithm of coarse fragment content of the B horizon (BCF) were used which explained 94 percent of the site index variation with less than one meter error. Both independent variables had normal distribution and the scatter plot of residuals indicated no systematic pattern and was satisfactory (Figure 3.6A). The scatter plot of the predicted versus actual site index values was shown in Figure 3.7A.

Table 3.13. Summary of the final multiple regression equations for sugar maple stands from the North Bay area utilizing the important variables from the CDA (Eq.3.9), and the simple linear regression analysis (Eq.3.10).

	Regression Equation	N	R^2	R^2_{adj}	SEE	p value
Eq.3.9	SI = 38.154 + 0.262 (HpHc) - 8.213 [log (BCF)]	15	0.940	0.925	0.979	0.000
Eq.3.10	SI = 7.056 + 2.997 (Asand/Asilt)	15	0.739	0.715	1.851	0.000

Where: SI = site index (m)
BCF = coarse fragment content in the B horizon (%)
HpHc = pH of saturated soil of the H horizon in $CaCl_2$ solution
Asand = sand content in the A horizon (%)
Asilt = silt content in the A horizon (%)

The scatter plots of residuals for both models were satisfactory (Figure 3. 6). Also, the trend graphs of predicted and actual site index values were illustrated in Figure 3.7 showing that the predicted and actual site index values scattered evenly along the line.

Eq.3.10 did include one variable which was the interaction between sand and silt content of the A horizon. Although, it explained only 74% of site index variation with about 1.9 meters error, all used variables could be obtained from the field and no laboratory analysis would be required. It must be noted that the data analysis process was performed only on 15 samples and in Eq.3.10 the variables came from A horizons which were generally very thin and, therefore, may not be fully representative of the full range of site index values. On the other hand, Eq.3.9 represented variables from two horizons

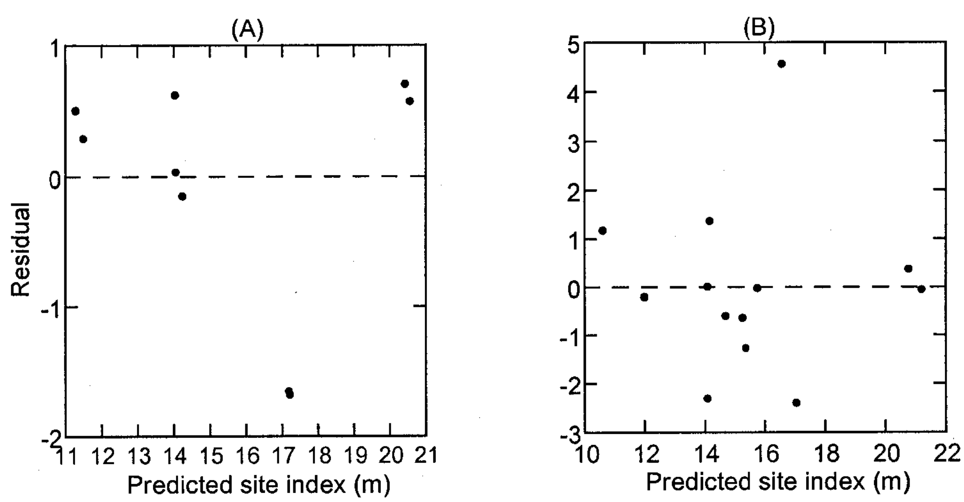

Figure 3.6. Scatter plots of residuals versus the predicted site indices of sugar maple stands from North Bay area. (A) Scatter plot of Eq. 3.9; (B) scatter plot of Eq. 3.10.

made more ecological sense in terms of site quality changes in sugar maple stands. For those reasons, Eq.3.9 might prove to be a better choice for predicting site index of sugar maple stands in the North Bay area.

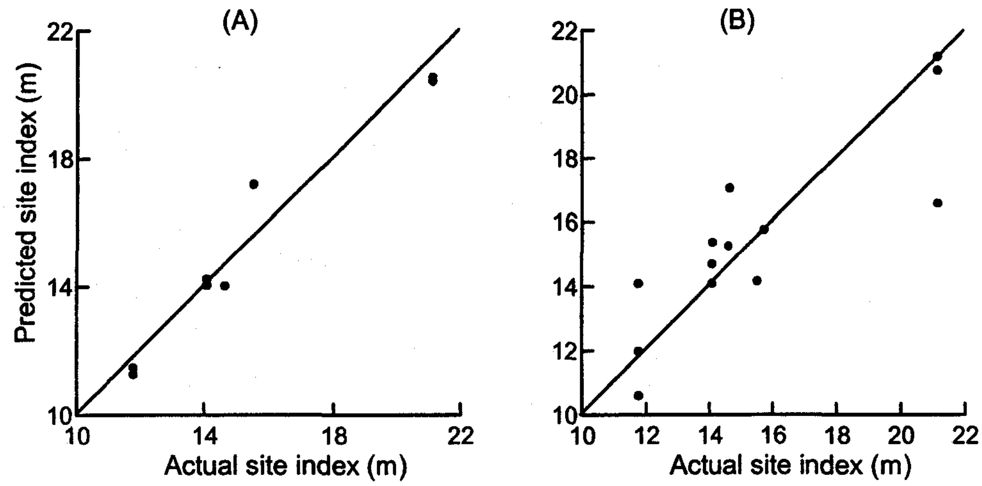

Figure 3.7. Predicted and measured site index values of sugar maple stands from North Bay area. (A) Scatter plot of Eq. 3.9; (B) scatter plot of NB. 3.10.

3.4.2. Soil-Sit Relationships for Red Oak

Canonical discriminant analysis was carried out and results showed that 88 percent of red oak samples were correctly reclassified into three site quality classes (Figure 3.8). Separation among site quality classes mainly occurred on the first canonical axis (99.5%). Also, the physical characteristics of soil in addition to topographic variable of elevation had the most weighting in order to discriminating the site quality classes of stands (Table 3.14).

Thickness and soil volume of the H horizon, coarse fragment content of the A horizon, along with elevation had absolute canonical coefficient values larger than 10 on the first canonical axis, while, the important variable on the second axis was thickness of the B horizon. N concentration in the H horizon (HNcon) and C concentration in the A horizon(ACcon), with canonical coefficients of -6.141 and -6.023, respectively, were more important than the other chemical characteristics. Their importance suggests that the site quality of red oak stands was more sensitive to organic matter content than other chemical factors.

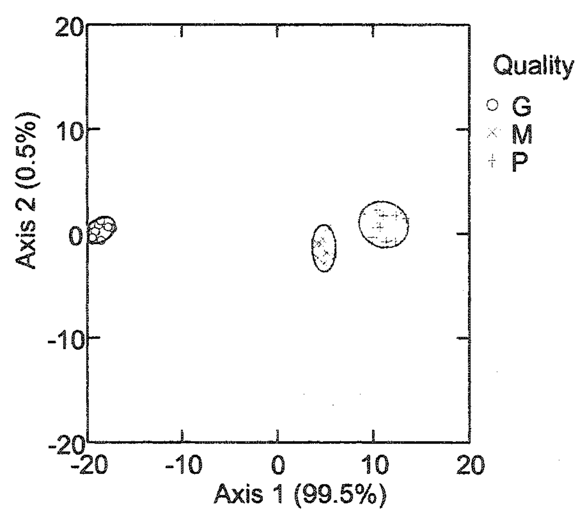

Figure 3.8. Canonical scores plot to discriminate site quality classes of red oak stands. The site quality groups included good (G); medium (M); and poor (P) sites. Variables included in discriminant function were elevation, nutrient concentrations, pH, C:N ratio of the H and A horizons, horizon thickness, coarse fragment content, bulk density, sand content of the A horizon, and the thickness and coarse fragment content of the B horizon.

Site indices were produced for eleven plots from all three regions for red oak stands. The minimum, maximum, range, and standard deviation of site indices for all regions together and each region separately were illustrated in Table 3.15.

Table 3.14. Standard canonical functions for good, medium, and poor sites of red oak stands.

Variable[1]	Standardized canonical functions coefficient		Variable	Standardized canonical functions coefficient	
	Canonical function 1	Canonical function 2		Canonical function 1	Canonical function 2
Elevation	10.507	0.411	Bthick	-1.547	10.377
HpHw[2]	-1.855	1.035	Hweight	11.553	3.792
HNcon	-6.141	2.125	Bweight	-2.208	-10.585
HPcon	2.562	-1.209	ACF	15.217	-2.662
ACcon	-6.023	2.823	BCF	-8.637	0.189
ANcon	4.301	-4.052	ADb	8.865	-1.740
AMgcon	3.719	-0.990	BDb	-4.264	1.973
ACN	-0.951	1.978	Bsand	-1.926	2.889
Hthick	-11.739	-4.400			

[1] Variables abbreviations were defined in Appendix II.
[2] pH values were converted to $[H^+]$ concentration prior to analysis.

Table 3.15. Summary of site index values of red oak stands. Data are from all three regions (C), Algonquin Park (AP), Haliburton Forest (HF), North Bay area(NB). Site index (SI_{BH50}) is total height of dominant and co-dominant trees at breast height age 50 years (Buda 2004).

Region	No of soil pits	Minimum	Maximum	Mean	Standard deviation
AP	12	10.6	13.2	11.5	1.1
HF	12	12.5	15.9	14.6	1.4
NB	9	15.4	18.1	16.9	1.2
Combined	33	10.6	18.1	14.1	2.5

A series of simple linear regressions were carried out to compare/contrast the relationships between site index of red oak and each of the independent variables. Those with significant probabilities and greater absolute values in their standard coefficients were illustrated in Table 3.16.

Table 3.16. Standard coefficient (SC), R^2, and the *p*-value of simple linear regression analysis between site index and independent variables of red oak stands.

Variable[1]	SC	R^2	*p*-value	Variable	SC	R^2	*p*-value
Elev*	-0.587	0.34	0.000	Bweight	0.433	0.19	0.003
ADb*	0.419	0.18	0.030	ACcon*	0.425	0.18	0.022
Asand	0.485	0.24	0.026	BCacon	-0.410	0.17	0.040
Asilt	-0.470	0.22	0.032	BMgcon	-0.443	0.20	0.021
BDb*	0.789	0.62	0.000	BMg	-0.415	0.17	0.040
Bsand*	0.807	0.65	0.000	BNacon	-0.323	0.10	0.047
Bsilt	-0.798	0.64	0.000				

[1] Variables abbreviations were defined in Appendix II.
[2] pH values were converted to $[H^+]$ concentration prior to analysis.
* Variable in common with canonical discriminant functions.

The physical characteristics including bulk density and texture of the mineral soil layers and soil volume of the B horizon had significant linear correlations with site index of red oak. Among them, bulk density of the A and B horizons and sand content of the B horizon were also influential in the CDA. Sand content in the both A and B horizons positively influenced site index of red oak which consequently resulted in a positive relationship with bulk density. In addition, elevation showed a significantly negative relationship with site index which had already been suggested as a strong factor in the site quality classification.

In terms of chemical characteristics, the simple regression analysis showed that the B horizon was more important than the other horizons in which, both concentration and pool size of Mg, along with the concentration of Ca and Na had negative linear relationships with site index. On the other hand, C concentration, the only important element from the A horizon, had a positive correlation with site index. This part, however, was not consistent with the CDA results which suggested nutrient concentrations in the H and A horizons did contribute to the weighting in site quality classification.

For preliminary multiple regression analysis five samples were once again randomly selected for model validation. From Table 3.14 those variables which had greater canonical coefficients including the plot elevation along with N concentration in the H horizon, coarse fragment content and bulk density in the B horizon, and C concentration in the A horizon, in addition to thickness and soil volume of the H and B horizons were selected and used in a stepwise, backward elimination, multiple regression analysis. All possible combinations of the independent variables were compared and evaluated, and Eq. 3.11 was selected as the best fit model (Table 3.17). In addition, the variables with greater standard coefficients from Table 3.15 were selected to create an alternative regression model, resulting in Eq.3.12 (Table 3.17).

Table 3.17. Summary of the best fit multiple regression equations for estimating red oak site index utilizing the important variables from the CDA (3.11), and the simple linear regression analysis (3.12).

	Regression Equation	N	R^2	R^2_{adj}	SEE	*p* value
Eq.3.11	SI = 2.879 + 0.246 (ACcon) +11.664(BDb)	22	0.758	0.734	1.118	0.000
Eq.3.12	SI = 24.506 - 3.173 [log(Bsilt/BDb)]	22	0.680	0.664	1.446	0.000

Where: SI = site index (m)
ACcon = C concentration in the A horizon (Mg g^{-1})
BDb = bulk density of the B horizon (gr cm^{-3})
Bsilt = silt percentage in the B horizon (%)

Both Equations from Table 3.17 were used to estimate site index for the validation and the results were summarized in Table 3.18. All 27 samples were regressed against site index values by using C concentration of A and bulk density of B horizon in Eq.2.13, and logarithm of silt content and bulk density of B horizon in Eq.3.14 (Table 3.19).

Table 3.18. Actual and predicted site indices of red oak stands for the verification data set (n=5) from all forest units using equation 3.11 and 3.12. Forest units including Algonquin Park (AP), Haliburton Forest (HF), and North Bay (NB).

Plot (soil pit)	SI Actual	SI predicted	Residual	SI predicted	Residual
		Eq.3.11		Eq.3.12	
AP 9(2)	11.6	13.2	-1.6	12.8	-1.2
AP 17(3)	10.6	12.5	-1.9	11.0	-0.4
HF 11(1)	14.3	13.9	0.3	13.7	0.6
HF 19(2)	15.9	14.7	1.2	14.3	1.7
NB 17(2)	18.2	18.8	-0.8	18.1	0.0

The scatter plot of residual versus predicted site indices for both Eq.3.13 (3.9.A), and 2.14 (3.9.B) were shown in Figure 3.9. The final models (Table 3.19) were used to plot the actual site indices versus the predicted site indices (Figure 3.10).

Table 3.19. Summary of the final multiple regression equations for red oak utilizing the important variables from the CDA (Eq.3.13), and simple linear regression analysis (Eq.3.14).

Regression Equation		N	R^2	R^2_{adj}	SEE	*p* value
Eq.3.13	SI = 2.628 + 0.262 (ACcon) + 11.724 (BDb)	27	0.730	0.707	1.179	0.000
Eq.3.14	SI = 21.258 - 1.859 [(logBsilt)/BDb]	27	0.732	0.721	1.343	0.000

Where: SI = site index (m)
ACcon = C concentration in the A horizon (Mg g^{-1})
BDb = bulk density of the B horizon (gr cm^{-3})
Bsilt = silt percentage in the B horizon (%)

The performance of both equations was similar, but, the scatter plot of residuals of Eq.3.14 was not quite satisfactory and showed that in the middle of site index range, the residuals tended to be larger compared to low and high site index values (Figure 3.9.B). Accordingly, Eq.3.13 was chosen as a better model for predicting site index for red oak.

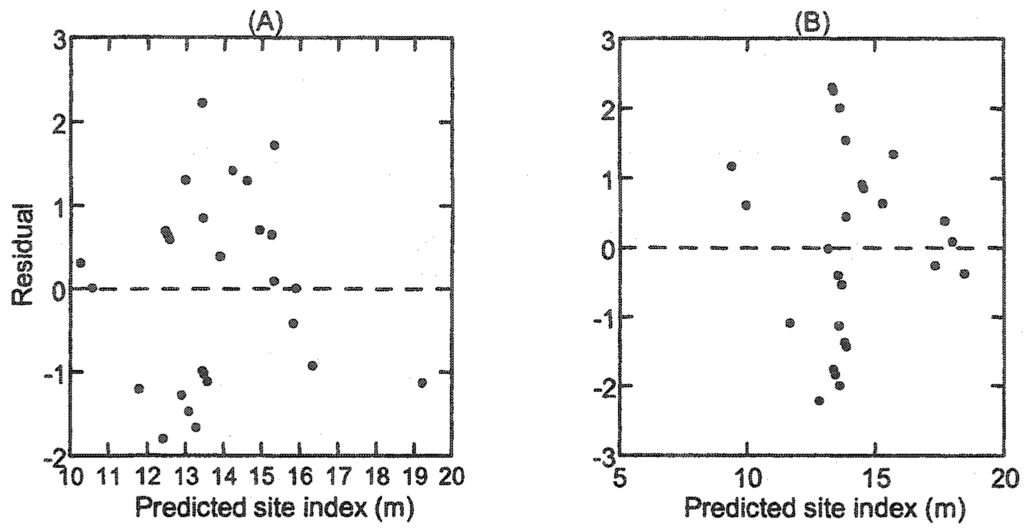

Figure 3.9. Scatter plots of residuals versus the predicted site indices of red oak stands. (A) Scatter plot of Eq.3.13.; (B) scatter plot of Eq.3.14.

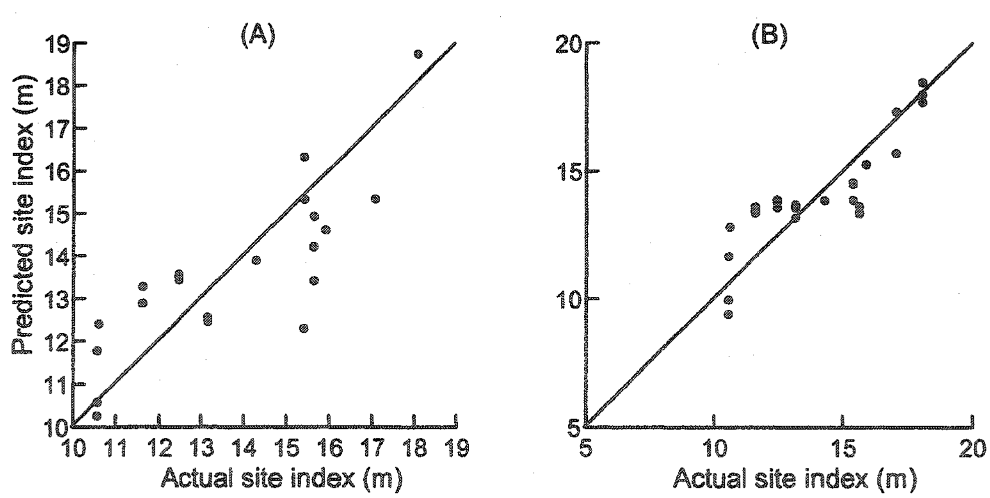

Figure 3.10. Predicted and measured site index values of red oak stands. (A) Scatter plot of Eq. 3.13; (B) scatter plot of Eq. 3.14.

3.4.3. Soil-Site Relationships for American Beech

It must be noted that the stem analysis revealed that some of beech samples had suffered from suppression during their lives, thus, the site index values used in this study might have some degree of inaccuracy (Buda 2004). In spite of that fact, CDA presented clear differentiation among three site quality classes of beech stands according to soil characteristics (Figure 3.11). The separation mainly occurred on the first canonical function, as it accounted for 75% of the total discrimination between the groups. pH, C:N ratio, Mg concentration, and soil volume of all three soil horizons, in addition to the nutrient concentrations in the H and B horizons along with bulk density, sand content of the A and B horizon, the thickness of the A horizon and the coarse fragment content in the B horizon were the most influential variables to separate the site quality classes (Table 3.20). Overall, 91(%) of site quality classes of beech stands were reclassified correctly.

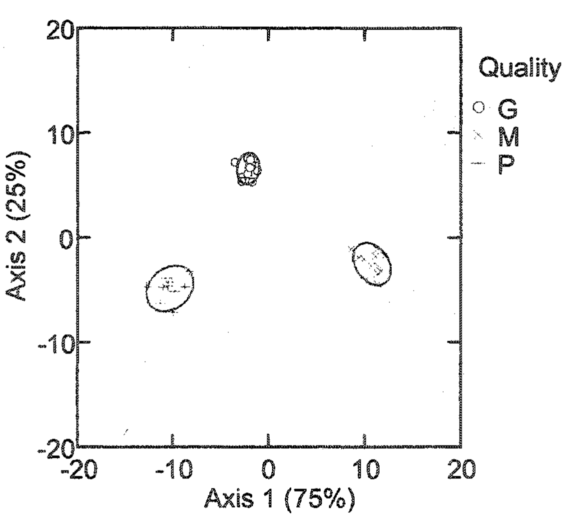

Figure 3.11. Canonical scores plotted to discriminate site quality classes of American beech stands. The site quality groups included good (G); medium (M); and poor (P) sites and variables were nutrient concentrations, pH, C:N ratio, horizon thickness, soil volume, and sand contents.

As previously noted, separation among three site quality classes occurred on the first canonical axis while the second axis, separated the good sites from other two classes. In the first function, the pH of the A and B horizon and the thickness and soil volume of the A horizon, along with C, N, and Ca concentration in the B horizon had canonical coefficients greater than 10 (Table 3.20). Only the C:N ratio and N concentration of the B

Table 3.20. Standard canonical functions for good, medium, and poor sites of American beech stands.

Variable[1]	Standardized canonical functions coefficient		Variable	Standardized canonical functions coefficient	
	Canonical function 1	Canonical function 2		Canonical function 1	Canonical function 2
HpHw[2]	-2.158	4.614	BPcon	-6.065	1.019
ApHw	-15.779	2.080	BCacon	-10.012	5.032
ApHc	13.576	-1.900	BMgcon	6.934	-2.962
BpHc	10.391	-0.255	BKcon	4.509	1.599
HCN	5.751	-3.141	Hweight	2.319	-2.428
BCN	-4.932	11.486	Athick	24.514	1.273
HCcon	-3.021	3.085	ADb	6.304	-2.139
HPcon	1.058	-4.564	Aweight	-24.139	-4.280
HMgcon	-5.782	3.136	Asand	4.233	3.627
HCacon	7.779	-4.232	Bweight	4.467	0.129
HNacon	2.202	-2.353	BCF	1.994	-1.009
AMgcon	-3.545	-1.453	BDb	7.677	1.288
BCcon	11.653	-9.903	Bsand	-1.985	-3.671
BNcon	-11.714	17.162			

[1] Variables abbreviations were defined in Appendix II.
[2] pH values were converted to $[H^+]$ concentration prior to analysis.

horizon had similar magnitudes on the second function. It seemed that the A horizon mostly contributed its effects on site quality differentiation through the physical characteristics. Finally, the nutrient contents of the H and B horizons were also important to the site quality of beech stands.

As for the other study species, simple linear regressions were carried out for each independent variable to determine those with stronger relationships with site index of beech. Those with significant probability were summarized in Table 3.21. The P concentration in the H and B horizons, C concentration, C:N ratio, coarse fragment, and

Table 3.21. Standard coefficient (SC), R^2, and the p-value of simple linear regression analysis between site index and independent variables of American beech stands.

Variable[1]	SC	R^2	p-value	Variable	SC	R^2	p-value
HPcon*	-0.277	0.08	0.097	BP	-0.629	0.40	0.000
HKcon	-0.329	0.12	0.044	BK	-0.447	0.20	0.008
HK	-0.309	0.10	0.059	ACF	0.510	0.26	0.001
AP	-0.323	0.10	0.051	BDb*	-0.366	0.13	0.033
APcon	-0.450	0.20	0.005	Bthick	-0.420	0.18	0.013
BCN*	0.551	0.30	0.001	BCF*	0.479	0.23	0.004
BCcon*	0.580	0.34	0.000	Bweight	-0.567	0.32	0.000
BPcon*	-0.553	0.31	0.001				

[1] Variables abbreviations were defined in Appendix II.
[2] pH values were converted to $[H^+]$ concentration prior to analysis.
* Variable in common with canonical discriminant functions.

soil volume of the B horizon were among those variables which had both significant Pearson correlation coefficients with site index and greater coefficients in CDA.

Five soil pits were deleted due to missing data and 7 were randomly chosen for model validation. Multiple regression analysis was, then, carried out using both the variables which had more weighting in the CDA and then using those variables which had stronger individual correlations with site index values. In the case of American beech, both approaches resulted the same best fit model, which included C concentration, coarse fragment content, and soil volume of the B horizon to explain the variation of site index (Table 3.22).

Table 3.22. The best fit multiple regression equation for American beech.

	Regression Equation	N	R^2	R^2_{adj}	SEE	*p* value
Eq.3.15	SI = 9.359 + 0.173 (BCF) - 0.001 (Bweight) + 0.917 (BCcon)	26	0.721	0.684	1.650	0.000

Where: SI = site index (m)
BCF = coarse fragment content in the B horizon (%)
Bweight = soil volume of the B horizon (ton. ha^{-1})
BCcon = C concentration in the B horizon (%)

The Eq.3.15 was used to estimate site index values for the validation data. Maximum absolute difference between actual and predicted site index values was 3.24, and the results were illustrated in Table 3.23.

Table 3.23. Actual and predicted site indices of American beech stands for the verification data set (n=5) from all forest units using equation 3.15. Forest units including Algonquin Park (AP), Haliburton Forest (HF), and North Bay (NB).

Plot (soil pit)	SI Actual	SI predicted	Residual
AP 22(2)	14.6	12.8	-1.8
AP 6(2)	13.0	13.7	0.7
AP 12(3)	9.1	12.3	3.2
HF 5(3)	17.2	16.2	-0.9
HF 12(1)	13.6	13.3	-0.3
HF 9(1)	13.0	13.4	0.4
HF 2(1)	9.1	10.6	1.5

As the final step, all 33 samples were used to generate a multiple regression equation using the independent variables of coarse fragment content, soil volume, and C concentration of the B horizon (Table 3.24: Eq.3.16).

Table 3.24. The final multiple regression equation for American beech.

Regression Equation		N	R^2	R^2_{adj}	SEE	*p* value
Eq.3.16	SI = 8.733 + 0.190 (BCF) - 0.001 (Bweight) + 0.966 (BCcon)	33	0.720	0.691	1.618	0.000

Where: SI = site index (m)
BCF = coarse fragment content in the B horizon (%)
Bweight = soil volume of the B horizon (ton. ha^{-1})
BCcon = C concentration in the B horizon (%)

The scatter plot of residuals versus predicted site index from Eq.3.16 was shown in Figure 3.12. The overall scatter plot was satisfactory and showed homoscedasticity of error variance. Also, the trend graph of predicted site index versus actual site index showed that the line situated generally in the centre of scatter plot and was satisfactory (Figure 3.13).

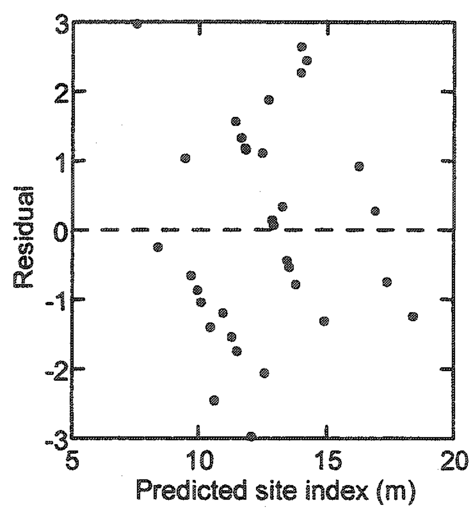

Figure 3.12. Scatter plot of residuals versus the predicted site indices of beech stands.

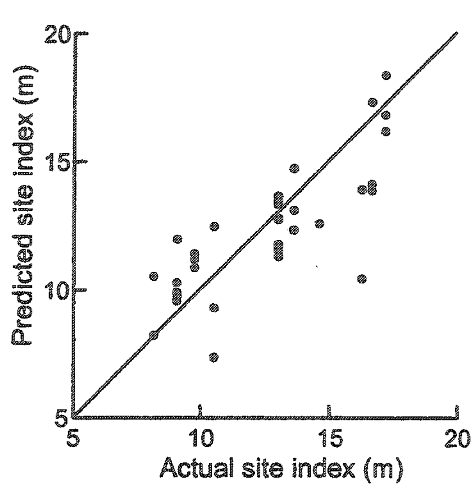

Figure 3.13. Predicted and measured site index values of beech stands.

3.5. DISCUSSION AND CONCLUSION

3.5.1. Sugar Maple

The site index values of sugar maple used in this study ranged between 8.3 and 20.8 m, while, the site index of this species in the Northern Wisconsin and upper Michigan which is currently used in central Ontario ranges between 12 and 28 m (Carmean 1978; OMNR 1998). The lower site index especially on the upper ends of site quality range might be due to the harsher environment in central Ontario compared to that in those states.

In Chapter 3, poor correlation between soil characteristics and site index values of sugar maple compared to red oak and beech dictated the necessity of sample plots stratification for sugar maple. Although, the stratification provided better results for the Haliburton Forest and North Bay area, the correlation between measured soil characteristics and site index values of sugar maple stands in Algonquin Park remained poor suggesting more studies. Overall, the sample plots in the Algonquin Park were located at higher average elevation (480.0 m) compared to those from the Haliburton Forest and North Bay area located at 401.0 and 382.0 m, respectively, above sea level.

In general, sugar maple performs best on soils with sandy loam, loamy sand, and silt loam textures and pH greater than 5.5 in upper layers (OMNR 1998). Although, the sand content in the A and B horizons from all sample plots were rather similar (i.e., sandy to sandy loam texture), the correlation between site index and sand content was significantly positive in both the Haliburton Forest and the North Bay area. Despite the relatively high level of sand in the mineral layers, it appeared that site index could still be improved by increasing sand content. In the Haliburton Forest and the North Bay area, the coarse fragment content of the A and B horizons also showed significant correlations with site index, although, it surprisingly had opposite influences at two areas. Texture is a fundamental factor controlling water and nutrient retention and uptake, as well as gas exchange (Schoenholtz *et al.* 2000). Sugar maple is sensitive to both drought and high levels of soil moisture (Skilling 1964; Westing 1966; Ward et al. 1966; and Horsley et al. 2002). Similar to the red oak stands, all sampling plots were located on shallow soils with an average depth of 36 cm and average annual precipitation rates between 550 to 1018 mm (MacKey *et al.* 1996). These amounts might be problematic, resulting in high water table at least for a period of time during the year. In this case, higher sand contents should increase drainage and eliminate the potential for saturated soil condition. In fact, Goodlett (1954) and Whitney (1990) found that in north western Pennsylvania and south western New York, sugar maple stands were associated with better drained, coarser textured, sandstone-derived soils, wherever the pH was low. It seemed that the physical characteristics of soil such as coarse fragment contents and texture which were indirectly related to the soil moisture content influenced effectively the growth of sugar maple in the region.

In the North Bay area, the pH of the H horizon was positively related to site index. As it was mentioned before, the optimum pH for sugar maple growth is 5.5 in the upper layers while the average pH of saturated soil in distilled water for the H, A, and B horizons were 4.6, 4.5, and 5.0, respectively. Accordingly, the site index of sugar maple in these two forest areas tended to be improved by increasing the pH. This was consistent with another study (Environment Canada 1990) suggesting that the poorer sites of sugar maple tended to be associated with low pH values. On the other hand, in the Haliburton Forest, pH of saturated soil in $CaCl_2$ of the A horizon was negatively related to site index.

In this case, the average pH of the A horizon was 4.3 and below the optimum level. The A horizon was thin with an average of 6.5 cm where the rooting system was usually absent. So, the A horizon played as a gateway where nutrients and water could move downward from the forest floor to the lower mineral layers. By increasing soil acidity, the cations such as Ca and Mg desorbed from colloids were leached where they could be absorbed by rooting systems of plants.

The pool of Na in the H horizon, C concentration in the A and B horizons from Haliburton Forest and the pool and concentration of Na in the B horizons from the Algonquin Park and North Bay area had significantly negative correlation with site index values. Although, the enhancement of Ca and Mg availability at the upper layers of soil improves the overall health conditions of sugar maple (e.g., mortality ratio, crown vigour, diameter and basal area growth, and flower and seed crop production) (Cote *et al.* 1993; Kolb and McCormick 1993; Coté *et al.* 1995; Wilmot *et al.* 1996; Long *et al.* 1997; van Breeman *et al.* 1997; Finzi *et al.* 1998; Bigelow and Canham 2002; Horsley *et al.* 2002), no significant correlation between those two nutrients and site index values of sugar maple was found. One might conclude that Ca and Mg are, in fact, at the optimum levels.

3.5.2. Red Oak

The range of site index values measured for red oak stands (10.6-18.1 m) was smaller than 12-24 m range suggested by Carmean (1978) for Northern Wisconsin and upper Michigan especially for upper ends of the range. Perhaps the harsher climatic norms of the northerly location made the site quality of red oak stands in central Ontario less productive and created such a great difference (6 m).

Elevation and site index values had a negative correlation where the good sites were located generally on average 313.50 m above sea level while the average elevation for medium and poor sites were 380.00 and 450.00 m, respectively. Carmean (1972) also found that the best sites of red oak stands were usually found on lower slopes. In this study however, aspect did not show any impact on site index.

Red oak is able to grow on a variety of soils, however, it grows the best on deep, moist and well drained soils with medium textures (Arend and Julander 1948, Westveld 1949, Gysel and Arend 1953, Sander 1957). In this study, the sample sites of red oak stands were, generally, located on shallow soils with average of 30 cm, with sandy to sandy loam textures (i.e., an average of 76% sand in the B horizon). Accordingly, the moisture regimes varied between dry and very rapidly to imperfectly drained to moderately fresh and well drained. So, in such a condition, the soil volume or the thickness of soil could be critical to plant growth by providing growing space for tree roots (Coile, 1952; Carmean, 1975). In fact, the data showed that the site quality improved with increasing mineral soil depth especially in the B horizon which was consistent with other studies (Trimble and Weitzman 1956; Bowersox and Ward 1972). The texture of the mineral soil is also important in determining the moisture content. In this case, the site index tended to improve with increasing sand content, which possibly improved drainage of the soils. The increasing sand content eventually increased soil bulk density which, in turn, also had a positive correlation with site index.

Although, the A horizon was generally thin (5.5 cm), its organic matter content had a significantly positive correlation with site index. Organic matter influences soil porosity, and thus gas exchange as well as water relations especially in such soils where there is a very small amount of clay. Furthermore, organic matter plays a critical role in carbon storage and cycling and strongly influences nutrient release and availability (Johnson, 1985; Henderson, 1995; Nambiar, 1997; Schoenholtz *et al.*, 2000).

The concentration of Ca, Mg, and Na in the B horizon had a significantly negative impact on site index of red oak. The pH value in the B horizon, on the other hand, was low. This was also the case for the H and A horizons (4.2-5.2 in distilled water and 4.0-5.0 in $CaCl_2$). In these acidic soils, greater amount of Ca and Mg would be displaced by H^+ and/or Al^{2+} ions from exchange sites and added into the soil solution which eventually would be absorbed by plants or leached (Brady 1990). This explanation, however, is not consistent with study made by Environment Canada (1990) suggesting that soils with lower pH tend to correspond to lower foliage levels of Ca and Mg. This discrepancy might be due to Al toxicity to roots in the upper soil horizons creating a negative correlation between Ca and Mg contents in the B horizon and site quality. The negative correlation between site index and Mg and Ca cations was not supported by what Bowersox and Ward (1972) found where the site index of oak sites in the ridge and valley region of Pennsylvania was positively correlated with those nutrients. However, inconsistency between two studies could be because of the differences of parent materials between Pennsylvania and central Ontario.

3.5.3. American Beech

The range of site index for American beech currently used in the region was 6 - 18 m (Carmean 1978) and the range which was found for this study was 8.17 - 17.17 m. The upper end of both ranges (good sites) match very well and there was only a small discrepancy in the poor sites.

American beech occurs in low elevations in the North, but up to 1800 m in the southern Appalachians (Rushmore 1961). In Central Ontario it is limited to the -12° C mean January isotherm (OMNR 1998). The sample sites in this study occupied a range of 410.0 - 530.0 m elevation from two forested areas of the Haliburton Forest and Algonquin Park. Aspect varied from north to northeast, east, and from south to southeast. Neither elevation nor aspect demonstrated significant relationship with site index.

The physical characteristics of the B horizon had stronger relationship with site index values of beech. American beech grows best on deep, well-drained, moist soils, with loamy texture and high humus content (Hutchinson 1918; Westveld 1933; Collingwood 1945; Elliot 1953; and Rushmore 1961). Somewhat contradictory to this, the increase in the B horizon thickness and soil volume around the rooting system tended to lower site quality of the beech stands. This unexpected behaviour was possibly related to beech's sensitivity to high ground water levels and prolonged flooding especially during the growing season (Hall and Smith 1955). As a result, the better quality stands tended to be situated on the upper slope and shallower sites. This might also explain the positive influence of coarse fragment content in the A and B horizons on site index that increased soil water infiltration in soil. Bulk density also had a negative impact on beech growth. In this case, the ability of rooting system to penetrate into the deeper soil layers reduces due to the increase in bulk density, accompanied by a decrease in porosity, and ultimately lowers the site quality.

C concentration and C/N ratio in the B horizon had a positive correlation with site index which is plausible since beech performs well on soils with high humus contents. American beech also occurs on podzolic and lateritic soils with richer subsoil layers (Cheyney 1942; Hamilton 1955; and Rushmore 1961). In this study, P in all three horizons were negatively correlated with site index of beech. Increasing P concentration could be related to soil moisture due to redox reduction with iron *i.e.*, Fe^{3+} to Fe^{2+} and PO^{3-} decrease. Accordingly, it could be the moisture content masking the relationships between P and site index.

3.5.4. Recommendation

It must be noted that this study was a preliminary step to understanding the soil characteristics and soil-site relations of the study species in the broad region of central Ontario. Therefore, the results must be applied and interpreted with caution and it must be noted that all measured variables in this study are only part of much bigger and more complex picture of tolerant hardwood forest ecosystems in the region. Accordingly, it may be worth to expand the future studies into:

1) the impacts of other micro nutrients such as iron and aluminium on site index and availability of other nutrients especially in acidic soils,

2) the nutrient availability by measuring the foliage nutrients and soil nutrient changes during a longer period of time. This will help to get a more comprehensive idea about the cycling of nutrients and their behaviour with respect to tree growth,

3) a closer look at deeper layers of soil profile (*i.e.*, BC and C horizons), which may reveal more information in terms of nutritional status,

4) identification of topographic and climatic patterns within a predetermined study area such as aspect, slope, and elevation to provide more consistent data which, in turn, can be used for stratification of sample sites, covariate, or as independent variables,

5) differences between pure and mixed wood stands to compare their performances with respect to nutritional cycling and site quality, and

6) a thorough understanding of moisture-ground water relationships with root physiology and identifying critical times of the season when moisture content has its most impact on site index.

Despite the recognition that most of the sample sites were located on shallow soils and the soil volume around the rooting system strongly influences total water and nutrients in the profile, except in the case of beech, depth of soil profile was not an influential factor in determining site quality. This may suggest that the study trees had not yet reached the restricted layers. It would follow that one might expect that as the stands aged the depth of the soil profile might become an important factor in determining site quality. In this case, the growth pattern may change dramatically, especially on the better sites. Accordingly, it might be reasonable to consider a greater index of age *e.g.*, 75 years of age, to produce more practical site index curves, especially for the longer-lived tolerant hardwood species.

3.5.5. Application of Models

All presented final models in this study have resulted from the data which originated from the described sample plots, thus they should be considered applicable only within the following geographic limitations:

1) within the geographic boundaries of each forested areas,

2) with no apparent evidence of any previous disturbances.

It should also be noted that the variables used in the various regression models had relatively high absolute values of coefficients with site index values. Therefore, all models are applicable within the sample sites as they were identified before. Moreover, all predictor variables used in final models must be obtained and measured by the mentioned field and laboratory methods (Section 2.3). Therefore, the following sampling protocols need to be adhered to:

1) the process of soil sample collection and preparation must be compatible with those explained here,

2) the maximum and minimum values of each independent variable should be within the range provided in Appendix III, and

3) the laboratory methodology must be followed as it was explained here.

CHAPTER 4. PRELIMINARY QUANTITATIVE CHARACTERIZATION OF NUTRIENT REGIMES FOR TOLERANT HARDWOOD FORESTS OF CENTRAL ONTARIO

4.1. INTRODUCTION

The forested landscape represents a heterogeneous area combining various forest ecosystems whose interrelations are in both temporal (*e.g.,* linked successional) and spatial scales and function, collectively, within the surrounding environment. In forests, the integration of biotic and abiotic factors forms different compositions and structures. The classification of forests is an attempt to overcome the complexity of the system and create a common language among people who manage them. Also, a practical classification of forest system should provide a comprehensible way to evaluate the sites for different purposes. Site quality evaluation is a crucial part of forest management as outlined in Chapter 2. Although, the term site quality evaluation and site classification are often used interchangeably, they do not have the same meaning. From a foresters' point of view, the productivity of forests is regarded, primarily, as merchantable wood volume on a per area basis. Although this concept has been modified slightly by incorporating other ecological forestry terms, it still remains as the mainstream issue in forestry. On the other hand, the classification of forest site provides a practical tool to group sites with common ecological attributes. In this case, these ecological groupings may or may not, depending on the original purpose of the classification, represent site productivity, particularly if the important factors driving productivity are not considered in the classification scheme.

In Ontario, forest ecosystem classification (FEC) is the main tool used to classify forests in most forested parts of the province. Although it provides an ecological homework that addresses fields such as silvicultural practices, stand composition and structure, moisture and drainage regimes, and wildlife habitat potential, its ability to explain productivity of commercial tree species has, in many cases, been marginal, at best (Schmidt and Carmean 1988, LeBlanc 1994, Carmean 1996). The lack of a quantitative soil nutrient regime, as part of the edatopic grid used in the ecosystem ordinations, represents another weak component of the FEC system.

Soil nutrient regime (SNR) is the amount of essential nutrients in the soil available to vascular plants over a period of time (Pojar *et al.* 1987). Problems involved in classification of nutrient gradient arise from uncertainty of identification of soil properties which can be used as differentiating characteristics (Courtin *et al.* 1988). The availability of nutrients is a function of many factors such as soil acidity, organic matters, texture, and climate which make the analytical process for quantifying it more complex. Accordingly, SNR classification has been based on forest floor and mineral soil morphological properties, physiographic site characteristics (parent material and landform) and vegetation (Courtin *et al.* 1988).

In this chapter, the objectives were 1) to identify nutrients having linear trend with site quality classes of any of study species, 2) to determine if soil moisture regime (SMR) can be used to identify soil nutrients, and 3) to develop a model for estimating total nitrogen from organic carbon. To do so, those nutrients which had significant influences on site indices of species (Tables 3.4; 3.8; 3.12; 3.16; and 3.21) were selected and their distributions across the site quality classes of three study species (Table 3.1) were examined. All of the nutrients were expressed in concentration in order to eliminate the influence of bulk density in their content values.

4.2. LITERATURE REVIEW

4.2.1. ENVIRONMENTAL FACTORS FOR SITE CLASSIFICATION

Climate is the most determinant factor in shaping the nature of ecosystems and it, within a regional scale, influences ecosystem over long periods of time. In spite of its importance, it can not be used solely in ecosystem classification due to the lack of data for large areas, the difficulties in measurement, and the uncertainty around identifying the critical climatic properties (Spurr and Barnes 1980; Pojar *et al.* 1987; Barnes *et al.* 1998). Moreover, local climate, which may vary from place to place within ecosystem units and relates better to site quality than regional climate, is strongly related to local topography and soil (Barnes *et al.* 1998). Accordingly, a classification system based on vegetation, topography and soil features should also encompass the local climatic characteristics of the site.

Within a given climatic region, physiographic features and soil condition are the most important factors influencing plant growth. The relationships between topography and site quality has been thoroughly investigated (Carmean 1975; Spurr and Barnes 1980; Barnes *et al.* 1998). Hills (1952) used physiographic features as the framework to classify ecosystems of Ontario which are discussed later.

4.2.2. VEGETATION AS AN INDICATOR OF SITE QUALITY

Vegetation can be used as an indicator of site quality assessment and site classification because it is the integrator of the whole ecosystem and expresses numerous environmental factors, and it is, also, easily observed at the site (Klinka 1989). The presence, abundance, and relative size of the various species may reflect the site quality

(Barnes *et al.* 1998). However, not always are the key species present in all sites, thus, the group of species with the same environmental requirements are grouped together. It should be also recognized that vegetation is continually changing over time (e.g., succession) which tends to make any forest classification based solely on vegetation composition less reliable (Pojar *et al.* 1987). In the boreal forest, where few dominant species are widespread over a variety of sites, the understory plants such as shrubs, herbs, and mosses become potentially suitable indicators. For example, Cajander (1926) used understory vegetation as a basis to rank the site qualities of pine, spruce, and birch stands in the boreal forest of Finland. He classified the height-growth curves of study species into site quality classes and then for each class the typical predominant species was presented. As a result, each site quality was represented by an indicator species. On a larger scale, the area can be classified into units according to vegetation to show the site quality differentiation.

4.2.3. BIOGEOCLIMATIC ECOSYSTEM CLASSIFICATION (BEC)

In British Columbia the biogeoclimatic ecosystem classification (BEC) is widely used to identify forest ecosystems based on climate, moisture, and nutrient attributes of a given site (Pojar *et al.* 1987; Kayahara and Pearson 1996). The BEC system characterizes the ecosystems at local, regional, and chronological scales (Pojar *et al.* 1987). At the local level, ecosystems are organized by similarities in their vegetation and site attributes producing vegetation and site units which are floristically uniform classes of plant communities. At the regional level, the ecosystems are organized in order to produce biogeoclimatic units which are "...geographically related ecosystems that are distributed within a vegetation-inferred climatic space" (Pojar *et al.* 1987). At the chronological level, the ecosystems are organized into site-specific chronosequences by arranging "... the vegetation units recognized for a given site unit according to disturbance, treatment, and successional status" (Pojar *et al.* 1987). The application and management interpretation of BEC has been explained in detail by Pojar and his colleagues (1987).

4.2.4. BADEN-WÜRTTEMBERG METHOD

The Baden-Wüttemberg method is a multiple classification approach used in Germany since 1946 (Barnes *et al.* 1982). The landscapes, first, are identified based on climate, geology, and vegetation which are called growth areas. Then, the heterogeneous growth areas are subdivided into more homogeneous growth districts based on microclimate, landform, soil, and vegetation. Finally, each growth district is divided into site units where the silvicultural practices, risk of damage (e.g., insects, fire, and windthrow), and growth and yield of forest trees are similar. Maps at approximately 1:10,000 scale illustrate the site units which are evaluated based on growth and productivity of important commercial tree species and are grouped together based on similar productivity levels (Barnes *et al.* 1982). The ground cover vegetation that indicates the similar conditions of local climate, moisture, nutrients, and pH are also classified (Spurr and Barnes 1980; Barnes *et al.* 1982). The silvicultural practices suggested for each site unit are prepared in comprehensive guides. These guides also include useful information about other aspects such as wildlife habitat, recreation management, landscape planning, etc.

4.2.5. HILLS' CLASSIFICATION OF ONTARIO'S FORESTS

Hills (1952 and 1966) classified forests of Ontario into seven "site regions". He briefly took five steps to establish his regional site classification: 1) providing a regional framework based on significant physiographic features including ecoclimate, soil moisture regimes, and soil nutrient regimes, 2) classifying the significant biological features or the organic portion of the environment within the physiographic framework, 3) recognition of human activities and their impacts on environment, 4) evaluating and rating the capability of the various physiographic sites to produce the important forest crops under various forest management scenarios, and 5) mapping the regions and other units across the province to show the distribution of physiographic, forest cover, and forest history *e.g.* fire, insect attack (Hills 1952).

Site regions, then, were subdivided into site types which were the combination of physiographic site types and forest types (Hills 1952). In the meantime, physiographic features remained the framework of classification due to their easy recognition in the field (Barnes *et al.* 1998).

4.2.6. FOREST ECOSYSTEM CLASSIFICATION IN ONTARIO

Ecological Land Classification is an ongoing project in Ontario to provide a common language for foresters and landscape managers (Chambers *et al.* 1997). Forest Ecosystem Classification (FEC) of central Ontario is part of that project which has built on the early classification work of Hills (1959). In this classification, any relatively undisturbed forest ecosystem can be classified into one of 25 ecosites (usually with .1 and .2 moisture class designations), 41 vegetation types, and 26 soil types.

To identify an ecosite, one needs to look at the overstory composition and the site conditions, which are largely based on moisture regime. The ecosite, then, leads the user to a descriptive section where the complete vegetation cover and soil-site features are explained in detail. The identification of a vegetation type is based on the tree species composition, regardless of the stratum they occur in. Soil types are identified based on soil depth, moisture regime, and texture.

4.2. RESEARCH METHOD

4.3.1. Data Collection

The process of data collection was the same as two previous chapters and described in section 3.3.

4.3.2. Data Analysis

The site index values were subjectively grouped into three site quality classes of good, medium and poor sites for each study species (Table 3.1). Those nutrients which had relatively stronger correlations with site index were selected (as they were in Chapter 3), and their mean values for each site quality class were computed. Among them, those nutrients with linear trends with site quality classes were chosen and compared with the soil moisture regimes to explore potential ways of quantifying/developing a soil nutrient regime which was in agreement with the SMR classification. Also, simple linear regression analyses were carried out between C and N concentration in each horizon to develop the best model for predicting total nitrogen in the soils of study area.

4.4. RESULTS

4.4.1. Comparison of Nutrient Concentration within Site Quality Classes of Species

Soil variables of C, N, C:N ratio, P, K and Na in the H horizon, C and P in the A horizon, and C, C:N ratio, P, Ca, Mg, and K in the B horizon were selected as nutrients which had significant correlation with site indices of three study species. In the H horizon, C, P, K concentration and C:N ratio under beech stands tended to increase while the site quality degraded. However, differences of mentioned characteristics among site quality classes were not always significant (Figure 4.1) and usually, good and poor stands had significant differences. In the case of C:N ratio, for instance, all site quality classes were statistically at the same level. Nutrients under sugar maple and red oak did not show any linear trend among site quality classes.

In the A horizon, P concentration under beech and red oak stands had a negative trend along with site quality classes. The difference was significant between good and poor classes. Also, C concentration of poor red oak stands was less than that in medium and good stands (Figure 3.2). C and P concentration showed no linear trend under sugar maple, although, there were curvilinear trends where poor and good sites were at the same levels and higher than that in medium sites.

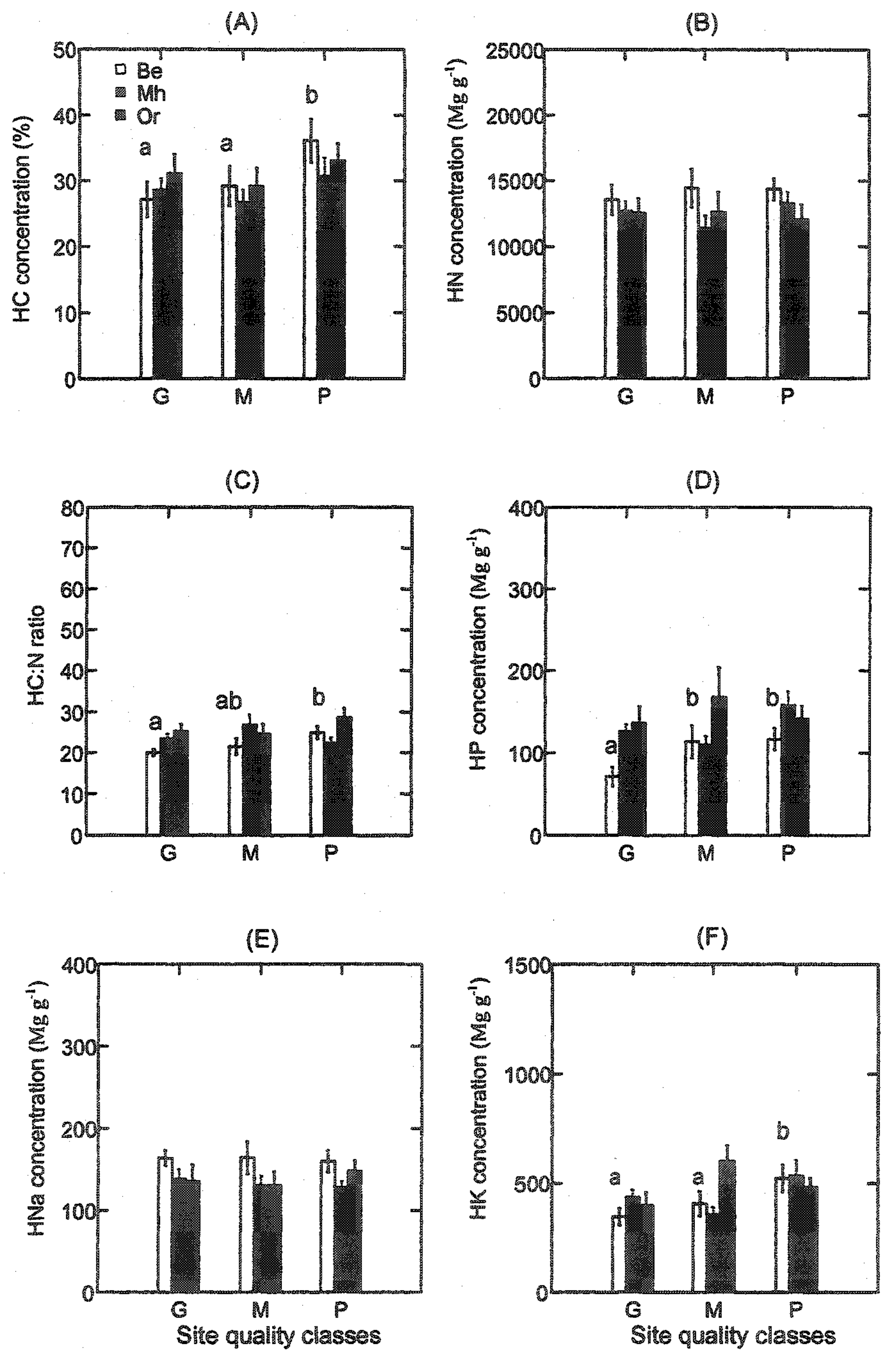

Figure 4.1. Distributions of C, N, P, Na, K concentrations and C:N ratio in the H horizon within site quality classes of American beech (Be), sugar maple (Mh), and red oak (Or). Values with the same subscript are not significantly different.

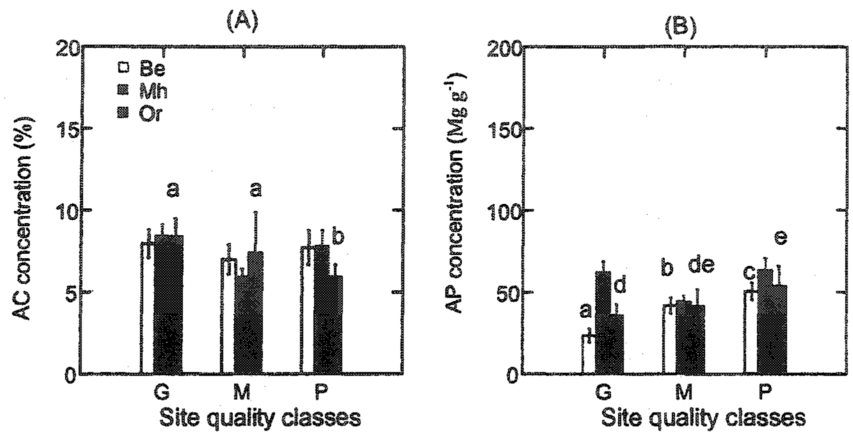

Figure 4.2. Distributions of C, and P, concentrations in the A horizon within site quality classes of American beech (Be), sugar maple (Mh), and red oak (Or). Values with the same subscript are not significantly different.

In the B horizon, C concentration under good sites of beech stands was higher than that in medium and poor sites followed by C:N ratio (Figure 4.3.A and B), while, P concentration showed increasing trend under both beech and sugar maple along with decreasing the site quality (Figure 4.3.C). Sugar maple, also, showed positive trends in Ca and Mg concentrations along with site quality classes (Figure 4.3D and E). Red ok had a decrease of K concentration when site quality improved. The means and standard errors of nutrients were illustrated in Table 4.1.

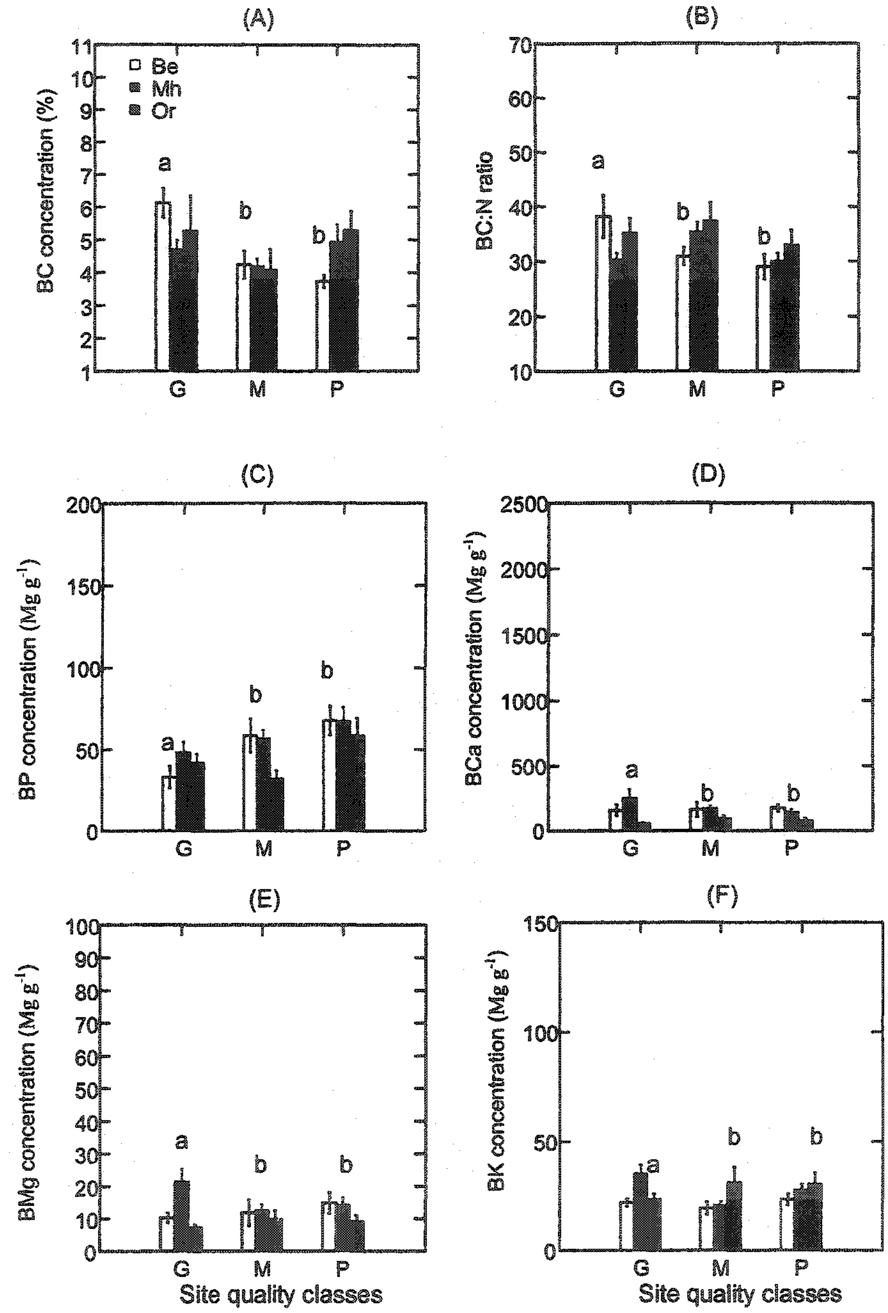

Figure 4.3. Distributions of C, P, Ca, and Mg concentrations and C:N ratio in the B horizon within site quality classes of American beech (Be), sugar maple (Mh), and red oak (Or). Values with the same subscript are not significantly different.

Table 4.1. Quantitative of nutrient concentration within site quality classes of good (G), medium (M), and poor (P) of study species. Values in parentheses are standard errors of means

Soil variables	American beech			Sugar maple			Red oak		
	G	M	P	G	M	P	G	M	P
HC (%)	**27.1**	**29.2**	**36.1**	28.6	26.7	30.7	29.1	33.0	31.0
	(2.5)	**(2.9)**	**(3.2)**	(1.7)	(1.8)	(2.6)	(2.6)	(2.6)	(2.8)
HN (Mg g^{-1})	13551.9	14428.6	14346.5	12683.1	11412.2	13313.1	12521.7	12590.1	12046.3
	(1089.0)	1382.6	788.9	(706.6)	(905.7)	(807.1)	(1062.2)	(1435.2)	(1086.6)
HC:N	20.0	21.5	24.9	23.5	26.869	22.6	25.2	24.6	28.6
	(0.7)	(1.9)	(1.5)	(1.1)	(2.4)	(1.1)	(1.7)	(2.2)	(2.3)
HP (Mg g^{-1})	**71.2**	**113.6**	**116.7**	126.1	110.2	158.9	136.5	167.7	142.0
	(11.1)	**(19.1)**	**(12.6)**	(8.5)	(10.3)	(16.2)	(19.1)	(33.9)	(14.8)
HK (Mg g^{-1})	**346.4**	**406.7**	**521.5**	436.3	358.1	534.6	398.6	599.9	482.2
	(36.9)	**(53.8)**	**(59.5)**	(31.5)	(32.2)	(69.5)	(56.7)	(67.8)	(39.6)
HNa (Mg g^{-1})	163.9	164.1	159.9	138.3	130.8	127.9	135.1	130.5	148.2
	(8.9)	(18.9)	(12.8)	(11.7)	(11.1)	(7.3)	(20.0)	(15.9)	(11.6)
AC (%)	7.9	7.0	7.7	8.4	5.9	7.8	**8.3**	**7.4**	**5.9**
	(0.8)	(0.8)	(0.9)	(0.7)	(0.4)	(0.9)	**(1.0)**	**(2.2)**	**(0.6)**
AP (Mg g^{-1})	**23.3**	**41.9**	**50.4**	62.3	44.2	63.5	35.8	41.4	53.8
	(3.9)	**(4.6)**	**(5.0)**	(6.5)	(3.6)	(7.0)	(6.1)	(9.3)	(11.4)
BC (%)	**6.1**	**4.2**	**3.7**	4.7	4.1	4.9	5.2	4.0	5.2
	(0.4)	**(0.4)**	**(0.1)**	(0.2)	(0.2)	(0.5)	(1.0)	(0.5)	(0.5)
BC:N	**38.2**	**30.9**	**29.0**	30.3	35.2	30.0	35.1	37.3	33.0
	(3.6)	**(1.5)**	**(2.1)**	(1.2)	(1.7)	(1.4)	(2.5)	(3.1)	(2.5)
BP (Mg g^{-1})	**33.0**	**58.7**	**67.9**	48.4	56.9	67.5	42.1	32.2	58.6
	(6.5)	**(9.8)**	**(8.5)**	(6.3)	(4.9)	(8.4)	(4.9)	(4.6)	(10.0)
BCa (Mg g^{-1})	155.7	160.4	172.3	**252.4**	**169.6**	**140.6**	56.3	91.5	74.5
	(40.8)	(52.4)	(25.8)	**(64.7)**	**(22.5)**	**(21.1)**	(6.2)	(20.0)	(17.9)
BMg(Mg g^{-1})	**10.2**	**11.8**	**14.8**	**21.4**	**12.5**	**14.2**	7.2	9.9	9.2
	(1.4)	**(3.8)**	**(3.0)**	**(3.9)**	**(1.7)**	**(2.2)**	(0.8)	(2.2)	(1.6)
BK (Mg g^{-1})	22.0	19.3	23.3	35.1	20.7	27.8	**23.3**	**31.0**	**30.3**
	(1.7)	(2.7)	(2.4)	(4.0)	(1.7)	(2.6)	**(2.5)**	**(6.6)**	**(4.8)**

The highlighted values are significantly different in a linear order.

4.4.2. Comparison of Nutrients within Soil Moisture Regime (SMR)

In the latter section, distributions of C, C:N ratio, P, and K in the H horizon, P in the A horizon, and C, P, Ca, and Mg in the B horizon had linear trend across site quality classes (mostly under beech stands). Distributions of these nutrients were, then, examined across

SMR. Although none of the cases in the H horizon showed significant linear trend, but C:N ratio and P concentration under beech stands had a slightly negative trend with increasing soil moisture content (Figure 4.4B and C). Since in red oak stands, only two SMR's were identified, it was not possible to define the general trends of nutrients along SMR.

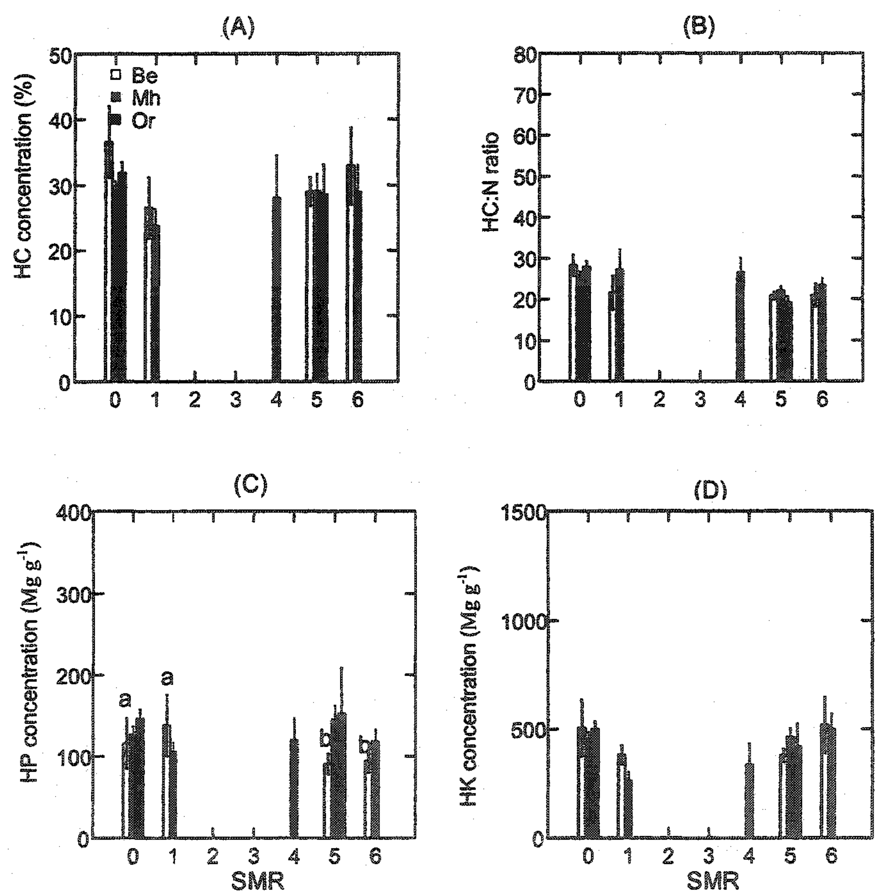

Figure 4.4. Distributions of C, P, and K concentrations and C:N ratio in the H horizon within soil moisture regime (SMR). Species included American beech (Be), sugar maple (Mh), and red oak (Or). Values with the same subscript are not significantly different.

In the A horizon, P concentration under sugar maple showed positive trend at the upper levels of water contents in the soil (4 and 6 SMR) (Figure 4.5.B).

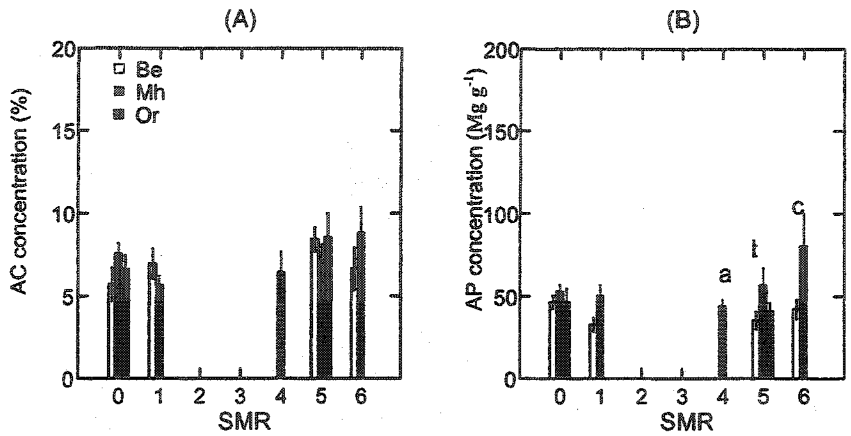

Figure 4.5. Distributions of P concentrations in the A horizon within soil moisture regime (SMR). Species included American beech (Be), sugar maple (Mh), and red oak (Or). Values with the same subscript are not significantly different.

In the B horizon, no obvious trend was found between nutrient gradients and SMR. However, some differences between two ends of SMR were visible. For example under beech stands, C concentration generally was lower in moderately dry and moderately fresh soils (0 and 1 SMR) compared to moist and very moist soils (5 and 6 SMR) (Figure 4.6.A) and conversely, P and Ca concentration was higher in drier soils than that in moist soils (Figure 4.6.B and C). These differences, however, were too inconsistent to be considered as a rule.

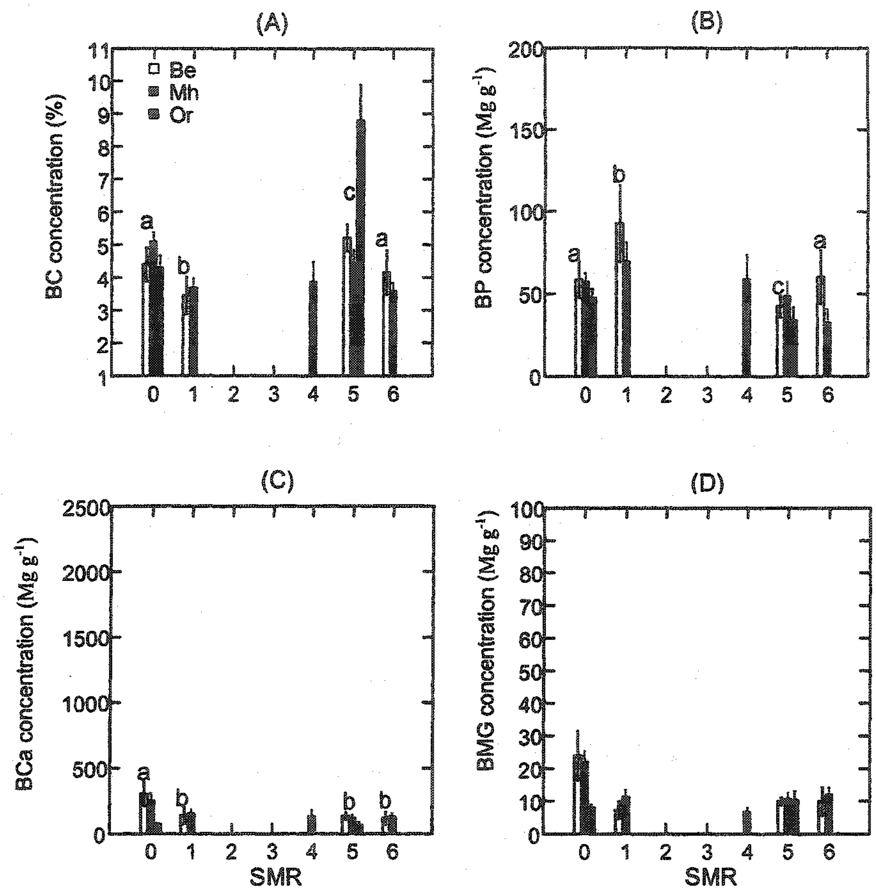

Figure 4.6. Distributions of C. P, Ca, and Mg concentrations in the B horizon within soil moisture regime (SMR). Species included American beech (Be), sugar maple (Mh), and red oak (Or). Values with the same subscript are not significantly different.

4.4.3. Estimation of Total Nitrogen Using Organic Carbon

Simple regression analyses showed strong positive correlation between C and total N concentration at each horizon separately, and all horizons together (Table 4.2.). The scatter plots of N concentrations vs. C concentrations were illustrated in Figure 4.7. Strong linear correlations between C and N were also found in all horizons (Eq.4.4).

Although its R^2 was quite larger than other equations (0.88), the regression produced a large standard error. Thus, equation 4.4 was not optimal for mineral horizons with lower C concentration range.

Table 4.2. Simple linear regression between N concentration and C concentration.

	Regression Equation	N	R^2	R^2_{adj}	SEE	*p* value
Eq. 4.1	HNcon = 3569.4 + 311.6 (HCcon)	161	0.549	0.546	2925.5	0.000
Eq. 4.2	AHcon = 74.24 + 490.37 (ACcon)	140	0.787	0.785	857.91	0.000
Eq.4.3	BHcon = 26.27 + 312.19 (BCcon)	138	0.732	0.730	331.21	0.000
Eq.4.4	Ncon = 323.70 + 408.53 (Ccon)	439	0.884	0.884	1943.2	0.000

Where: HNcon = concentration of N in the H horizon (Mg g^{-1})
HCcon = concentration of C in the H horizon (%)
ANcon = concentration of N in the A horizon (Mg g^{-1})
ACcon = concentration of C in the A horizon (%)
BNcon = concentration of N in the B horizon (Mg g^{-1})
BCcon = concentration of C in the B horizon (%)
Ncon = concentration of N in all horizons (Mg g^{-1})
Ccon = concentration of C in all horizons (%)

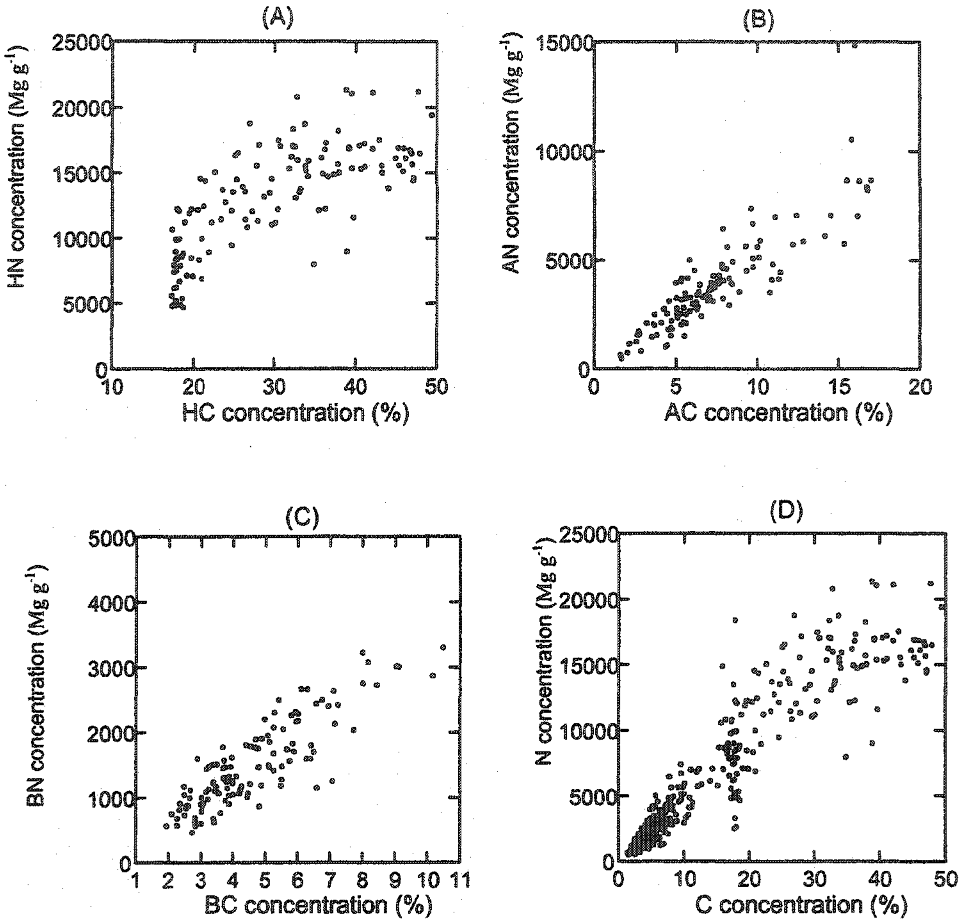

Figure 4.7. Scatter plots of N concentration versus C concentration in the H, A, B horizons and all horizons together.

4.5. DISCUSSION AND CONCLUSION

Under American beech stands there were more distinctive nutrient differences along with site quality classes than sugar maple and red oak stands. Accordingly it seemed that beech was the best species indicator for connecting site quality and SNR. Also, two elements; C and P concentrations in all three horizons showed somewhat linear trends with site quality classes of beech (except C concentration in the A horizon which had a trend under red oak stands). While P concentration always had a negative trend with increasing site quality, C concentration in the H horizon was negatively and in the B horizon positively correlated with site quality classes. Therefore, P concentration under beech stands could be the best candidate for the basis of a quantitative soil nutrient regime. Although, pH and C:N ratio had been suggested as the most useful differentiating characteristics for humus form classes (Courtin *et al.* 1988) they did not showed any potential (C:N ratio was not significantly different and pH had no linear trend) to be used in classifying soil nutrients. On the other hand, strong correlation between C and N and the relatively usefulness of C in quantifying SNR might indicate some potential for using nitrogen, but this would require more study.

In terms of the comparison of SMR's and site indices, there was no evidence indicating a systematic trend in site quality along with the soil moisture catena. SMR of sample plots did not show any clear relationships with the changes in critical nutrient contents. However, more studies with a range of plots including the whole range of SMR may reveal some relationships between water and nutrient contents.

Identified soil moisture regimes could be combined into two main groups, one with water deficit including moderately dry and moderately moist, and the other with no water deficit including moderately to very moist soils (Kayahara and Pearson 1996). Beech stands showed significantly differences in site indices between the two soil moisture regimes ($p < 0.05$). In the same way, two soil moisture regimes were compared in terms of nutrients and as a result, and the pool and concentration of P, along with the pool of K in the B horizon under beech were significantly different ($p<0.05$). These results, with some exceptions, however, were too inconsistent to be used in relating SMR to nutrients and site quality.

If the productivity of sites becomes a basis for classifying SNR's across central Ontario, those elements which are critical for growth, at least for the main commercial species, must be considered in quantifying soil nutrient regimes. None of the nutrients measured in this study was critical for the three study species. As a general statement, organic matter, which is strongly correlated to C, N, and C:N ratio, P and Na is a prime candidate for future studies. These elements usually play a role in site productivity in either forms of concentration or pool size for any of the soil horizons. Nitrogen-related variables are especially important and numerous studies have supported their roles in site quality and characterization of nutrient regimes (Kayahara and Pearson 1996, Barnes *et al.* 1998, Chen *et al.* 1998b, Splechtna and Klinka 2000).

This study compared assessment of the soil nutrients with SMR in order to quantify/compare the existing classification (SMR) and relate it to site quality across the region. However, it was uncertain whether those measured elements reflected real availability of nutrients to the plants. To better quantify SNR's for the region, foresters and researchers should answer some initial questions, including, 1) which laboratory method provides a more realistic measurement of nutrients in the soil, 2) which group of nutrients is more critical for growth of commercial tree species at a regional scale, 3) which soil horizon is more important in terms of plant uptake, and 4) is concentration or pool size a better reflection of nutritional status. Although in this study, all attempts were made to provide the best possible data, because of the extensive scale of the region and the difficulties of sampling in uneven-aged mixedwood stands not all of these questions could be addressed.

Since, in central Ontario a field classification of forested ecosystems has been established and used, any classification of nutrient regimes should be developed within that framework. To do so, the ecosites, vegetation types, or soil types described in "Field Guide to Forest Ecosystems of Central Ontario" should be used to stratify sampling designs for future studies on the nutritional characteristics of these site types and the quantification of a soil nutrient regime for the region.

CHAPTER 5. CONCLUSION

In Chapter 2, most of the differences occurred between beech and red oak in terms of nutrient variability, while, sugar maple was either associated with beech or red oak. In general, beech occurred on lower ends of P gradient in all horizons and upper ends of N in the H and A horizons and Ca, Mg,, and Na gradients in the mineral layers. Sugar maple, on the other hand, occurred on soil with higher P and Ca in the A and B horizons and lower Na in all horizons. Finally, red oak unlike beech occurred on lower P in the A and B horizons and lower N in the H horizon, and lower Ca, Mg, and Na in the A and B horizons.

The data from sugar maple stands, in the third chapter, were stratified into three groups in order to create stronger correlation between site index values and soil characteristics. In the majority of sample plots (Haliburton Forest and North Bay area), total N in the H horizon indicating N nitrification rate was influential on the site quality of sugar maple. Also, strong correlation between site index values and texture and coarse fragment contents in the mineral layers suggested that the moisture content had strong influence on the site quality of sugar maple. In terms of red oak and beech, results from simple regression analysis showed no necessity for data stratification. In terms of red oak, texture of the mineral layers significantly influenced the site index suggesting a strong relationship between soil moisture content and site quality of that species. Also, cation contents in the B horizon were among the most important soil nutrients affecting the red oak growth in the region. Beech, on the other hand, was generally more sensitive to coarse fragment contents in mineral soil which like other two species might be due to the influence of coarse fragment on moisture contents. Phosphorus, also, was the most important nutrient affecting site index of beech in the region.

The approach toward a preliminary SNR in Chapter 4 showed that P concentration in both organic and inorganic layers under beech stands was the most promising candidate for creating a SNR which was able to indicate the site quality as well. However, attempts to connect any nutritional quantification to soil moisture regime (SMR) were failed which showed more studies are necessary to quantify a practical SNR in the region.

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APPENDICES

APPENDIX I

Summary of equations used for modification of chemical properties

The original concentrations of N, P, Ca, Mg, Na, and K were modified by subtracting the moisture content from soil samples:

$$NC = NC' - (NC' * M.C.) \qquad \text{(Eq. A1.1)}$$

where: NC = nutrient concentration (Mg g^{-1})
NC′ = nutrient content before subtracting moisture (Mg g^{-1})
M.C. = moisture content (%)

the pool of nutrients (kg ha^{-1}) were, then, measured by Equation A1.2.

$$NP = [h - (h * C.F.)] * Db * NC * 10 \qquad \text{(Eq. A1.2)}$$

where: NP = nutrient content (kg ha^{-1})
h = thickness of horizon (m)
C.F. = coarse fragment (%)
Db = bulk density (gr cm^{-3})
NC = nutrient concentration (Mg g^{-1})

The same process was done for organic carbon content (Eq. A1.3):

$$CP = [(h * 10000) - (h * 10000 * C.F.)] * Db * 1000 * C \qquad \text{(Eq. A1.3)}$$

where: CP = organic carbon content (kg ha^{-1})
h = thickness of horizon (m)

C.F. = coarse fragment (%)

Db = bulk density (gr cm^{-3})

C = organic carbon concentration (percent)

$$M.H. = [(N.C._1 * h_1) + (N.C._2 * h_2)]/h_1 + h_2 \quad \text{(Eq. A1.4)}$$

where: M.H = nutrient content of major horizon (kg ha^{-1})

$N.C._1$ = nutrient content of first horizon (kg ha^{-1})

$N.C._2$ = nutrient content of second horizon (kg ha^{-1})

h_1 = thickness of first horizon (m)

h_1 = thickness of second horizon (m)

$$M.pH = -\log(((10\text{^}-(pH_1) * h_1 * Db_1) + (10\text{^}-(pH_2) * h_2 * Db_2))/(h_1+h_2)) \quad \text{(Eq. A1.5)}$$

where: M.pH = pH of major horizon

pH_1 = pH of first horizon

pH_2 = pH of second horizon

APPENDIX II

List of variables and their abbreviations

A. Dependent variables:

SI	Site index ($BHSI_{50}$)

B. Independent variables:

1. <u>Topography:</u>

Elev.	Altitude of plot above sea level (m)
Slope	Crest, Upper slope, middle slope, Lower slope, Toe, Depression, Level

2. <u>Soil particles:</u>

HCF	Coarse fragment content in the H horizon (%)
ACF	Coarse fragment content in the A horizon (%)
BCF	Coarse fragment content in the B horizon (%)
Asand	Sand content in the A horizon (%)
Asilt	Silt content in the A horizon (%)
Aclay	Clay content in the A horizon (%)
Bsand	Sand content in the B horizon (%)
Bsilt	Silt content in the B horizon (%)
Bclay	Clay content in the B horizon (%)

3. Soil volume and bulk density:

HDb	Bulk density of the H horizon (gr cm^{-3})
Hweight	Soil volume of the H horizon (kg ha^{-1})
ADb	Bulk density of the A horizon (gr cm^{-3})
Aweight	Soil volume of the A horizon (kg ha^{-1})
BDb	Bulk density of the B horizon (gr cm^{-3})
Bweight	Soil volume of the B horizon (kg ha^{-1})

4. Depth and thickness:

Depth	Depth of rooting system (cm)
Hthick	Thickness of the H horizon (cm)
Athick.	Thickness of the A horizon (cm)
Bthick.	Thickness of the B horizon (cm)

5. Soil acidity:

HpHw	pH of saturated soil in distilled water from the H horizon
HpHc	pH of saturated soil in $CaCl_2$ solution from the H horizon
ApHw	pH of saturated soil in distilled water from the A horizon
ApHc	pH of saturated soil in $CaCl_2$ solution from the A horizon
BpHw	pH of saturated soil in distilled water from the B horizon
BpHc	pH of saturated soil in $CaCl_2$ solution from the B horizon

6. Nutrient pool:

HC	Pool of organic carbon in the H horizon (ton.ha^{-1})
HN	Total nitrogen in the H horizon (kg ha^{-1})

HCN	C/N ratio in the H horizon
HP	Pool of phosphorus in the H horizon (kg ha^{-1})
HMg	Pool of magnesium in the H horizon (kg ha^{-1})
HCa	Pool of calcium in the H horizon (kg ha^{-1})
HNa	Pool of sodium in the H horizon (kg ha^{-1})
HK	Pool of potassium in the H horizon (kg ha^{-1})
AC	Pool of organic carbon in the A horizon (ton.ha^{-1})
AN	Total nitrogen in the A horizon (kg ha^{-1})
ACN	C/N ratio in the A horizon
AP	Pool of phosphorus in the A horizon (kg ha^{-1})
AMg	Pool of magnesium in the A horizon (kg ha^{-1})
ACa	Pool of calcium in the A horizon (kg ha^{-1})
ANa	Pool of sodium in the A horizon (kg ha^{-1})
AK	Pool of potassium in the A horizon (kg ha^{-1})
BC	Pool of organic carbon in the B horizon (ton.ha^{-1})
BN	Total nitrogen in the B horizon (kg ha^{-1})
BCN	Carbon-nitrogen ratio in the B horizon
BP	Pool of phosphorus in the B horizon (kg ha^{-1})
BMg	Pool of magnesium in the B horizon (kg ha^{-1})
BCa	Pool of calcium in the B horizon (kg ha^{-1})
BNa	Pool of sodium in the B horizon (kg ha^{-1})
BK	Pool of Potassium in the B horizon (kg ha^{-1})

7. Nutrient concentration:

HCcon	Organic carbon content in the H horizon (%)
HNcon	Nitrogen concentration in the H horizon (Mg g^{-1})
HPcon	Phosphorus concentration in the H horizon (Mg g^{-1})
HMgcon	Magnesium concentration in the H horizon (Mg g^{-1})
HCacon	Calcium concentration in the H horizon (Mg g^{-1})

HNacon	Sodium concentration in the H horizon (Mg g^{-1})
HKcon	Potassium concentration in the H horizon (Mg g^{-1})
ACcon	Organic carbon percentage in the A horizon (%)
ANcon	Nitrogen concentration in the A horizon (Mg g^{-1})
APcon	Phosphorus concentration in the A horizon (Mg g^{-1})
AMgcon	Magnesium concentration in the A horizon (Mg g^{-1})
ACacon	Calcium concentration in the A horizon (Mg g^{-1})
ANacon	Sodium concentration in the A horizon (Mg g^{-1})
AKcon	Potassium concentration in the A horizon (Mg g^{-1})
BCcon	Organic carbon percentage in the B horizon (%)
BNcon	Nitrogen concentration in the B horizon (Mg g^{-1})
BPcon	Phosphorus concentration in the B horizon (Mg g^{-1})
BMgcon	Magnesium concentration in the B horizon (Mg g^{-1})
BCacon	Calcium concentration in the B horizon (Mg g^{-1})
BNacon	Sodium concentration in the B horizon (Mg g^{-1})
BKcon	Potassium concentration in the B horizon (Mg g^{-1})

Appendix III

Summary of soil physical and chemical properties within site quality classes of study species

Table A3.1. Quantitative of nutrient concentration and pH of the H, A, and B horizons within site quality classes of good (G), medium (M), and poor (P) of study species. Values in parentheses are standard errors of means.

Soil nutrient concentration	American beech			Sugar maple			Red oak		
	G	M	P	G	M	P	G	M	P
HpHw	4.6	4.5	4.6	4.6	4.8	4.5	4.6	4.4	4.6
	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.2)
HpHc	4.0	4.3	4.3	4.2	4.3	4.2	4.1	3.9	4.3
	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.2)	(0.2)	(0.2)
HC (%)	27.1	29.2	36.1	28.6	26.7	30.7	29.1	33.0	31.0
	(2.5)	(2.9)	(3.2)	(1.7)	(1.8)	(2.6)	(2.6)	(2.6)	(2.8)
HN (Mg g^{-1})	13551.9	14428.6	14346.5	12683.1	11412.2	13313.1	12521.7	12590.1	12046.3
	(1089.0)	1382.6	788.9	(706.6)	(905.7)	(807.1)	(1062.2)	(1435.2)	(1086.6)
HP (Mg g^{-1})	71.2	113.6	116.7	126.1	110.2	158.9	136.5	167.7	142.0
	(11.1)	(19.1)	(12.6)	(8.5)	(10.3)	(16.2)	(19.1)	(33.9)	(14.8)
HCa (Mg g^{-1})	3094.3	3480.5	3614.0	2953.8	2991.0	3250.3	2841.7	2587.8	3788.8
	(723.0)	(571.9)	(399.2)	(250.5)	(315.5)	(379.4)	(406.9)	(475.5)	(511.7)
HMg (Mg g^{-1})	289.0	303.3	373.2	305.7	263.8	338.1	295.6	325.5	377.5
	(50.1)	(35.9)	(42.2)	(23.9)	(20.6)	(36.4)	(32.3)	(40.2)	(30.9)
HK (Mg g^{-1})	346.4	406.7	521.5	436.3	358.1	534.6	398.6	599.9	482.2
	(36.9)	(53.8)	(59.5)	(31.5)	(32.2)	(69.5)	(56.7)	(67.8)	(39.6)
HNa (Mg g^{-1})	163.9	164.1	159.9	138.3	130.8	127.9	135.1	130.5	148.2
	(8.9)	(18.9)	(12.8)	(11.7)	(11.1)	(7.3)	(20.0)	(15.9)	(11.6)
ApHw	4.5	4.5	4.6	4.5	4.5	4.5	4.3	4.0	4.2
	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.)	(0.1)
ApHc	4.2	4.4	4.3	4.2	4.4	4.3	4.0	3.9	4.1
	(0.1)	(0.1)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.2)	(0.1)

Soil nutrient concentration	American beech			Sugar maple			Red oak		
	G	M	P	G	M	P	G	M	P
AC (%)	7.9	7.0	7.7	8.4	5.9	7.8	8.3	7.4	5.9
	(0.8)	(0.8)	(0.9)	(0.7)	(0.4)	(0.9)	(1.0)	(2.2)	(0.6)
AN (Mg g^{-1})	3374.4	3817.5	4404.2	4134.9	2971.8	4552.8	3905.6	3230.6	2982.1
	(474.6)	(339.1)	(721.3)	(348.4)	(277.4)	(754.0)	(791.6)	(889.2)	(578.5)
AP (Mg g^{-1})	23.3	41.9	50.4	62.3	44.2	63.5	35.8	41.4	53.8
	(3.9)	(4.6)	(5.0)	(6.5)	(3.6)	(7.0)	(6.1)	(9.3)	(11.4)
ACa (Mg g^{-1})	480.7	514.8	671.2	755.6	567.3	614.3	310.6	461.1	607.3
	(140.1)	(74.2)	(98.8)	(124.0)	(77.2)	(65.9)	(70.9)	(150.3)	(157.7)
AMg (Mg g^{-1})	43.5	57.2	74.2	81.8	66.9	82.8	54.3	73.5	62.5
	(7.2)	(6.4)	(8.2)	(10.6)	(13.1)	(8.2)	(10.2)	(23.9)	(9.8)
AK (Mg g^{-1})	76.6	91.2	107.7	115.412	93.373	131.173	103.037	138.422	92.567
	(11.3)	(8.0)	(12.0)	(11.0)	(16.8)	(15.9)	(17.3)	(42.8)	(12.1)
ANa (Mg g^{-1})	151.568	136.406	126.8	115.6	125.4	101.9	114.7	94.3	121.2
	(4.3)	(9.1)	(14.8)	(10.6)	(9.8)	(8.6)	(16.3)	(25.9)	(5.5)
BpHw	5.0	5.1	5.0	5.0	5.0	4.8	4.8	4.8	4.8
	(0.1)	(0.1)	(0.1)	(0.1)	(0.0)	(0.1)	(0.0)	(0.1)	(0.1)
BpHc	4.5	4.6	4.5	4.4	4.5	4.3	4.4	4.3	4.5
	(0.1)	(0.1)	(0.1)	(0.1)	(0.0)	(0.1)	(0.1)	(0.1)	(0.1)
BC (%)	6.1	4.2	3.7	4.7	4.1	4.9	5.2	4.0	5.2
	(0.4)	(0.4)	(0.1)	(0.2)	(0.2)	(0.5)	(1.0)	(0.5)	(0.5)
BN (Mg g^{-1})	1816.8	1412.4	1321.8	1646.7	1283.6	1666.7	1568.8	1171.1	1737.8
	234.3	145.7	93.3	132.9	96.1	159.9	317.8	255.8	250.6
BP (Mg g^{-1})	33.0	58.7	67.9	48.4	56.9	67.5	42.1	32.2	58.6
	(6.5)	(9.8)	(8.5)	(6.3)	(4.9)	(8.4)	(4.9)	(4.6)	(10.0)
BCa (Mg g^{-1})	155.7	160.4	172.3	252.4	169.6	140.6	56.3	91.5	74.5
	(40.8)	(52.4)	(25.8)	(64.7)	(22.5)	(21.1)	(6.2)	(20.0)	(17.9)
BMg (Mg g^{-1})	10.2	11.8	14.8	21.4	12.5	14.2	7.2	9.9	9.2
	(1.4)	(3.8)	(3.0)	(3.9)	(1.7)	(2.2)	(0.8)	(2.2)	(1.6)
BK(Mg g^{-1})	22.0	19.3	23.3	35.1	20.7	27.8	23.3	31.0	30.3
	(1.7)	(2.7)	(2.4)	(4.0)	(1.7)	(2.6)	(2.5)	(6.6)	(4.8)
BNa (Mg g^{-1})	135.3	123.5	123.7	101.4	114.2	97.2	82.2	64.1	107.7
	(6.3)	(5.6)	(13.3)	(10.1)	(10.9)	(9.2)	(18.1)	(19.7)	(4.6)

Table A3.2. Quantitative of pool of nutrients of the H, A, and B horizons within site quality classes of good (G), medium (M), and poor (P) of study species. Values in parentheses are standard errors of means.

Soil nutrient	American beech			Sugar maple			Red oak		
pool	G	M	P	G	M	P	G	M	P
HC	31.6	22.7	40.2	27.8	22.4	25.8	29.0	26.4	27.6
(ton ha^{-1})	(7.6)	(3.4)	(6.3)	(3.1)	(1.7)	(4.1)	(7.2)	(4.5)	(2.5)
HN	1599.8	1099.7	1591.7	1159.1	951.5	1074.	1105.4	1112.5	1033.3
(kg ha^{-1})	(396.4)	(150.3)	(237.5)	(101.1)	(80.5)	(130.3)	(234.3)	(194.3)	(126.0)
HC:N	20.0	21.5	24.9	23.5	26. 9	22.6	25.2	24.6	28.6
	(0.7)	(1.9)	(1.5)	(1.1)	(2.4)	(1.1)	(1.7)	(2.2)	(2.3)
HP	7.9	8.2	13.2	11.0	9.1	12.5	11.4	14.7	12.1
(kg ha^{-1})	(2.0)	(1.5)	(2.1)	(0.9)	(0.9)	(1.7)	(2. 1)	(3.2)	(1.6)
HCa	298.9	252.9	379.6	268.9	252.9	265.4	226.3	254.2	330.7
(kgha^{-1})	(71.2)	(47.9)	(52.8)	(27.7)	(30.5)	(44.3)	(36.2)	(81.8)	(59.6)
HMg	28.8	21.9	39.3	27.9	22.1	27.6	23.7	29.412	32.1
(kg ha^{-1})	(5.11)	(2.6)	(5.3)	(2.6)	(1.9)	(4.3)	(3.3)	(5.8)	(3.7)
HK	30.9	29.9	55.2	40.1	29.4	38.4	32.7	54.7	41.3
(kg ha^{-1})	(3.1)	(4.6)	(7.9)	(3.5)	(2.6)	(5.7)	(5.5)	(9.7)	(4.9)
HNa	19.2	12.8	16.2	12.9	10.4	9.9	11.3	11.5	12.5
(kg ha^{-1})	(4.5)	(2.0)	(1.7)	(1.5)	(0.9)	(0.9)	(2.6)	(1.5)	(1. 2)
AC	41.0	38.1	39.1	34.2	23.2	31.9	41.3	24.4	24.0
(ton ha^{-1})	(7.0)	(10.3)	(9.0)	(7.6)	(2. 1)	(6.5)	(20.2)	(9.2)	(7.9)
AN	1552.3	1872.6	1992.8	1596.0	1094.7	1563.7	1553.7	1130.5	1316.8
(kg ha^{-1})	(247.4)	(494.5)	(421.6)	(303.9)	(97.6)	(262. 7)	(616. 7)	(417.1)	(485.5)
AC:N	26.1	22.1	18.7	20.8	22.1	18.5	24.5	24.7	24.3
	(2.0)	(3.9)	(0.9)	(0.8)	(1.3)	(1.0)	(3.2)	(2.6)	(3.1)
AP	10.9	14.1	15.9	22.9	17.8	23.4	12.9	15.9	24.1
(kg ha^{-1})	(1.6)	(1.7)	(1.9)	(3.7)	(2.1)	(3.6)	(3.0)	(6.7)	(12.5)
ACa	265.5	195.7	327.6	268.3	276.7	263.6	121.1	143.4	287.6
(kg ha^{-1})	(85.1)	(28.1)	(96.4)	(54.9)	(71. 2)	(67.1)	(40.3)	(68. 4)	(138.6)
AMg	19.8	22.3	35.9	27.8	25.8	32.3	24.4	22.1	25.6
(kg ha^{-1})	(4. 6)	(3.0)	(9.6)	(4.2)	(6.2)	(6.9)	(11.2)	(7.6)	(9.6)
AK	32.4	37.8	51.0	43.3	37.5	49.1	43.2	46.4	39.2
(kg ha^{-1})	(4. 7)	(5.4)	(12.8)	(8.0)	(8.3)	(9.6)	(16.3)	(18.5)	(15.7)

Soil nutrient pool	American beech			Sugar maple			Red oak		
	G	M	P	G	M	P	G	M	P
ANa ($kg\ ha^{-1}$)	87.9 (17.1)	56.9 (9.6)	59.7 (10.8)	53.2 (9.9)	52.3 (5.8)	39.9 (5.9)	54.4 (26. 3)	33.3 (16.3)	41.6 (10.5)
BC ($ton\ ha^{-1}$)	100.1 (10.6)	67.8 (10.1)	83.7 (8.7)	86.4 (7.3)	84.3 (6.6)	107.6 (15.3)	115.8 (17.4)	66.4 (16.3)	87.4 (11.7)
BN ($kg\ ha^{-1}$)	3054.6 (485.4)	2196.6 (324.4)	3080.8 (454.4)	3039.6 (293.4)	2631.3 (248.3)	3617.8 (498.1)	3402.7 (539.3)	1967.4 (650.9)	2834.8 (467.3)
BC:N	38.2 (3.6)	30.9 (1.5)	29.0 (2.1)	30.3 (1.2)	35.2 (1.7)	30.0 (1.4)	35.1 (2.5)	37.3 (3.1)	33.0 (2.5)
BP ($kg\ ha^{-1}$)	63.9 (15.1)	94.4 (20.2)	151.1 (15.9)	85.7 (11.4)	118.0 (14.3)	137.6 (18.8)	121.0 (22.2)	51.9 (9.0)	98.7 (20.4)
BCa ($kg\ ha^{-1}$)	239.7 (60.7)	250.1 (80.9)	383.1 (68.8)	429.5 (95.6)	336.3 (44.0)	299.9 (56.5)	204.0 (63.9)	176.0 (37.3)	394.4 (117.1)
BMg ($kg\ ha^{-1}$)	16.3 (2.4)	18.6 (6.0)	33.9 (7.6)	36.3 (5.5)	24.8 (3.3)	30.7 (5.6)	17.1 (2.0)	22.5 (4.8)	20.4 (5.0)
BK($kg\ ha^{-1}$)	62.9 (19.2)	122.3 (27.8)	157.8 (48.6)	65.2 (7.8)	42.0 (4.6)	61.2 (8.7)	58.5 (9.3)	45.7 (7.0)	63.0 (12.4)
BNa ($kg\ ha^{-1}$)	199.1 (29.7)	103.5 (26.6)	171.8 (35.0)	173.8 (21.2)	214.4 (20.6)	195.9 (22.5)	181.6 (45.6)	109.7 (38.2)	164.3 (22.9)

Table A3.3. Quantitative of physical properties of the H, A, and B horizons within site quality classes of good (G), medium (M), and poor (P) of study species. Values in parentheses are standard errors of means.

Soil physical properties	American beech			Sugar maple			Red oak		
	G	M	P	G	M	P	G	M	P
Hthick (cm)	5.1	3.1	5.2	4.4	3.9	3.7	4.2	4.4	3.9
	(1.3)	(0.5)	(0.6)	(0.3)	(0.2)	(0.4)	(0.9)	(0.5)	(0.4)
Hvolume (ton ha^{-1})	121.9	77.6	113.1	95.4	84.8	83.5	90.5	91.9	86.6
	(30.9)	(7.2)	(13.1)	(7.3)	(4.3)	(8.4)	(19.3)	(11.6)	(7.3)
Athick (cm)	8.6	5.7	7.1	6.1	6.7	6.4	6.1	4.7	5.5
	(1.7)	(1.1)	(1.2)	(0.9)	(1.0)	(1.4)	(2.4)	(1.4)	(1.6)
ACF (%)	4.7	5.3	3.9	10.5	9.8	6.7	8.7	8.2	10.6
	(0.7)	(0.9)	(0.9)	(1.5)	(2.1)	(1.6)	(2.3)	(2.5)	(1.4)
ADb (gr cm^{-3})	0.7	0.8	0.7	0.7	0.8	0.7	0.7	0.8	0.7
	(0.0)	(0.0)	(0.1)	(0.0)	(0.0)	(0.0)	(0.1)	(0.0)	(0.0)
Avolume (ton ha^{-1})	601.7	451.8	483.2	424.8	487.3	440.2	473.2	333.7	345.0
	(130.6)	(84.5)	(88.9)	(68.3)	(69.7)	(93.1)	(181.9)	(100.3)	(95.0)
Asand (%)	62.3	72.8	66.0	67.7	68.6	66.6	73.2	71.6	68.6
	(2.9)	(2.2)	(1.5)	(1.6)	(1.3)	(2.3)	(3.8)	(3.3)	(2.0)
Asilt (%)	34.8	24.5	31.0	29.5	28.9	30.2	24.1	26.8	30.6
	(2.8)	(2.1)	(1.6)	(1.5)	(1.3)	(2.3)	(3.7)	(3.4)	(2.8)
Aclay (%)	3.0	2.7	3.0	2.8	2.5	3.3	2.7	1.7	3.0
	(0.3)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.4)	(0.2)	(0.2)
Bthick (cm)	27.3	30.3	34.5	28.4	30.5	31.2	29.6	21.9	27.2
	(2.7)	(3.3)	(3.3)	(1.9)	(1.7)	(2.7)	(3.5)	(2.1)	(2.4)
BCF (%)	9.2	6.8	4.1	9.5	10.5	8.1	9.6	11.4	9.4
	(2.2)	(1.9)	(0.9)	(1.4)	(2.0)	(2.1)	(1.3)	(2.4)	(1.2)
BDb (gr cm^{-3})	0.8	0.9	0.8	0.8	0.9	0.8	1.0	0.8	0.7
	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.1)	(0.0)	(0.0)
Bvolume (ton ha^{-1})	1910.0	2330.1	2741.6	2101.3	2284.4	2184.6	2699.7	1563.1	1776.8
	(221.5)	(256.6)	(270.6)	(153.5)	(123.5)	(160.7)	(344.5)	(158.5)	(164.5)

Soil physical properties	American beech			Sugar maple			Red oak		
	G	M	P	G	M	P	G	M	P
Bsand (%)	65.7	74.9	67.8	67.7	71.0	64.6	83.6	73.7	69.9
	(2.0)	(3.3)	(3.4)	(2.2)	(1.7)	(3.4)	(2.7)	(1.4)	(2.2)
Asilt (%)	31.6	23.7	30.8	30.5	27.0	33.9	15.0	24.8	29.2
	(2.0)	(3.3)	(3.3)	(2.2)	(1.7)	(3.3)	(2.5)	(1.8)	(2.3)
Bclay (%)	2.7	1.4	1.6	1.8	2.0	1.5	1.5	1.5	1.8
	(0.3)	(0.3)	(0.4)	(0.2)	(0.2)	(0.3)	(0.5)	(0.4)	(0.4)